6. Agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. This chapter provides an assessment of non-carbon-dioxide emissions from the following source categories: enteric fermentation in domestic livestock, livestock manure management, rice cultivation, agricultural soil management, and field burning of agricultural residues (see Figure 6-1). Carbon dioxide (CO_2) emissions and removals from agriculture-related land-use activities, such as conversion of grassland to cultivated land, are presented in the Land Use, Land-Use Change, and Forestry chapter. CO_2 emissions from on-farm energy use are accounted for in the Energy chapter.

Figure 6-1: 2005 Agriculture Chapter Greenhouse Gas Emission Sources

In 2005, the agricultural sector was responsible for emissions of 536.3 teragrams of CO_2 equivalent (Tg CO_2 Eq.), or 7 percent of total U.S. greenhouse gas emissions. Methane (CH_4) and nitrous oxide (N_2O) were the primary greenhouse gases emitted by agricultural activities. CH_4 emissions from enteric fermentation and manure management represent about 21 percent and 8 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation and field burning of agricultural residues were minor sources of CH_4. Agricultural soil management activities such as fertilizer application and other cropping practices were the largest source of U.S. N_2O emissions, accounting for 78 percent. Manure management and field burning of agricultural residues were also small sources of N_2O emissions.

Table 6-1 and Table 6-2 present emission estimates for the Agriculture sector. Between 1990 and 2005, CH_4 emissions from agricultural activities increased by 4 percent, while N_2O emissions fluctuated from year to year, but overall decreased by less than 1 percent. In addition to CH_4 and N_2O, field burning of agricultural residues was also a minor source of the indirect greenhouse gases carbon monoxide (CO) and nitrogen oxides (NO_x).

Table 6-1: Emissions from Agriculture (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**154.4**	**164.0**	**160.5**	**161.0**	**161.2**	**161.1**	**158.7**	**161.2**
Enteric Fermentation	115.7	120.6	113.5	112.5	112.6	113.0	110.5	112.1
Manure Management	30.9	35.1	38.7	40.1	41.1	40.5	39.7	41.3
Rice Cultivation	7.1	7.6	7.5	7.6	6.8	6.9	7.6	6.9
Field Burning of Agricultural Residues	0.7	0.7	0.8	0.8	0.7	0.8	0.9	0.9
N_2O	**375.9**	**362.7**	**386.9**	**399.2**	**376.2**	**359.9**	**348.7**	**375.1**
Agricultural Soil Management	366.9	353.4	376.8	389.0	366.1	350.2	338.8	365.1
Manure Management	8.6	9.0	9.6	9.8	9.7	9.3	9.4	9.5
Field Burning of Agricultural Residues	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5
Total	**530.3**	**526.8**	**547.4**	**560.3**	**537.4**	**521.1**	**507.4**	**536.3**

Note: Totals may not sum due to independent rounding.

Table 6-2: Emissions from Agriculture (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**7,353**	**7,811**	**7,643**	**7,668**	**7,678**	**7,673**	**7,556**	**7,674**
Enteric Fermentation	5,510	5,744	5,404	5,356	5,361	5,379	5,262	5,340
Manure Management	1,471	1,673	1,844	1,911	1,959	1,928	1,892	1,966

Rice Cultivation	339	363	357	364	325	328	360	328
Field Burning of Agricultural Residues	33	32	38	37	34	38	42	41
N_2O	**1,213**	**1,170**	**1,248**	**1,288**	**1,213**	**1,161**	**1,125**	**1,210**
Agricultural Soil Management	1,184	1,140	1,215	1,255	1,181	1,130	1,093	1,178
Manure Management	28	29	31	32	31	30	30	31
Field Burning of Agricultural Residues	1	1	1	1	1	1	2	2
CO	**691**	**663**	**792**	**774**	**709**	**800**	**879**	**858**
NO_x	**28**	**29**	**35**	**35**	**33**	**34**	**39**	**39**

Note: Totals may not sum due to independent rounding.

6.1. Enteric Fermentation (IPCC Source Category 4A)

CH_4 is produced as part of normal digestive processes in animals. During digestion, microbes resident in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process, referred to as enteric fermentation, produces CH_4 as a by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted by an individual animal depends primarily upon the animal's digestive system, and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive system. Ruminants possess a rumen, or large "fore-stomach," in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized. The microbial fermentation that occurs in the rumen enables them to digest coarse plant material that non-ruminant animals cannot. Ruminant animals, consequently, have the highest CH_4 emissions among all animal types.

Non-ruminant domesticated animals (e.g., swine, horses, and mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine. These non-ruminants emit significantly less CH_4 on a per-animal basis than ruminants because the capacity of the large intestine to produce CH_4 is lower.

In addition to the type of digestive system, an animal's feed quality and feed intake also affects CH_4 emissions. In general, lower feed quality or higher feed intake lead to higher CH_4 emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types as well as among different management practices for individual animal types.

CH_4 emission estimates from enteric fermentation are provided in Table 6-3 and Table 6-4. Total livestock CH_4 emissions in 2005 were 112.1 Tg CO_2 Eq. (5,340 gigagrams [Gg]), increasing slightly since 2004 due to minor increases in most animal populations and dairy cow milk production in all regions. Beef cattle remain the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71 percent in 2005. Emissions from dairy cattle in 2005 accounted for 25 percent, and the remaining emissions were from horses, sheep, swine, and goats.

From 1990 to 2005, emissions from enteric fermentation have decreased by 3 percent. Generally, emissions have been decreasing since 1995, mainly due to decreasing populations of both beef and dairy cattle and improved feed quality for feedlot cattle. During this timeframe, populations of sheep have decreased by an average annual rate of about 4 percent per year while horse, goat, and swine populations have remained relatively constant.

Table 6-3: CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq.)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005
Beef Cattle	81.0	87.4	81.3	80.3	80.2	80.5	78.3	79.2
Dairy Cattle	28.9	27.7	27.0	26.9	27.1	27.3	27.0	27.7
Horses	1.9	1.9	2.0	2.0	2.0	2.0	2.0	2.0
Sheep	1.9	1.5	1.2	1.2	1.1	1.1	1.0	1.0
Swine	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Goats	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Total	**115.7**	**120.6**	**113.5**	**112.5**	**112.6**	**113.0**	**110.5**	**112.1**

Note: Totals may not sum due to independent rounding.

Table 6-4: CH_4 Emissions from Enteric Fermentation (Gg)

Livestock Type	1990	1995	2000	2001	2002	2003	2004	2005
Beef Cattle	3,859	4,160	3,869	3,825	3,821	3,832	3,730	3,772
Dairy Cattle	1,375	1,320	1,283	1,280	1,288	1,299	1,285	1,319
Horses	91	92	94	95	95	95	95	95
Sheep	91	72	56	55	53	51	49	49
Swine	81	88	88	88	90	90	91	91
Goats	13	12	12	12	13	13	13	13
Total	**5,510**	**5,744**	**5,404**	**5,356**	**5,361**	**5,379**	**5,262**	**5,340**

Note: Totals may not sum due to independent rounding.

Methodology

Livestock emission estimates fall into two categories: cattle and other domesticated animals. Cattle, due to their large population, large size, and particular digestive characteristics, account for the majority of CH_4 emissions from livestock in the United States. A more detailed methodology (i.e., IPCC Tier 2) was therefore applied to estimate emissions for all cattle except for bulls. Emission estimates for other domesticated animals (horses, sheep, swine, goats, and bulls) were handled using a less detailed approach (i.e., IPCC Tier 1).

While the large diversity of animal management practices cannot be precisely characterized and evaluated, significant scientific literature exists that describes the quantity of CH_4 produced by individual ruminant animals, particularly cattle. A detailed model that incorporates this information and other analyses of livestock population, feeding practices and production characteristics was used to estimate emissions from cattle populations.

National cattle population statistics were disaggregated into the following cattle sub-populations:

- Dairy Cattle
    - Calves
    - Heifer Replacements
    - Cows
- Beef Cattle
    - Calves
    - Heifer Replacements
    - Heifer and Steer Stockers
    - Animals in Feedlots (Heifers and Steers)
    - Cows
    - Bulls

Calf birth rates, end of year population statistics, detailed feedlot placement information, and slaughter weight data were used to model cohorts of individual animal types and their specific emissions profiles. The key variables tracked for each of the cattle population categories are described in Annex 3.9. These variables include performance factors such as pregnancy and lactation as well as average weights and weight gain. Annual cattle population data were obtained from the U.S. Department of Agriculture's National Agricultural Statistics Service (1995a,b; 1999a,c,d,f,g; 2000a,c,d,e; 2001a,c,d,f; 2002a,c,d,f; 2003a,c,d,f; 2004a,c,d,f, 2005a-d, 2006a-d).

Diet characteristics were estimated by region for U.S. dairy, beef, and feedlot cattle. These estimates were used to calculate Digestible Energy (DE) values and CH_4 conversion rates (Y_m) for each population category. The IPCC recommends Y_m values of 3.5 to 4.5 percent for feedlot cattle and 5.5 to 6.5 percent for other well-fed cattle consuming temperate-climate feed types. Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed, rather than using the recommended IPCC values. The diet characterizations and estimation of DE and Y_m values were based on information from state agricultural extension specialists, a review of published forage quality studies, expert opinion, and modeling of animal physiology. The diet characteristics for dairy cattle were from Donovan (1999), while those for beef cattle were derived from NRC (2000). DE and Y_m for dairy cows were calculated from diet characteristics using a model simulating ruminant digestion in growing and/or lactating cattle (Donovan and Baldwin 1999). For feedlot animals, DE and Y_m values recommended by Johnson (1999) were used. Values from EPA (1993) were used for dairy replacement heifers. For grazing beef cattle, DE values were based on diet information in NRC (2000) and Y_m values were based on Johnson (2002). Weight data were estimated from Feedstuffs (1998), Western Dairyman (1998), and expert opinion. See Annex 3.9 for more details on the method used to characterize cattle diets in the United States.

To estimate CH_4 emissions from cattle, the population was divided into region, age, sub-type (e.g., dairy cows and replacements, beef cows and replacements, heifer and steer stockers, and heifer and steer in feedlots), and production (e.g., pregnant, lactating) groupings to more fully capture differences in CH_4 emissions from these animal types. Cattle diet characteristics were used to develop regional emission factors for each sub-category. Tier 2 equations from IPCC (2000) were used to produce CH_4 emission factors for the following cattle types: dairy cows, beef cows, dairy replacements, beef replacements, steer stockers, heifer stockers, steer feedlot animals, and heifer feedlot animals. To estimate emissions from cattle, population data were multiplied by the emission factor for each cattle type. More details are provided in Annex 3.9.

Emission estimates for other animal types were based on average emission factors representative of entire populations of each animal type. CH_4 emissions from these animals accounted for a minor portion of total CH_4 emissions from livestock in the United States from 1990 through 2005. Also, the variability in emission factors for each of these other animal types (e.g., variability by age, production system, and feeding practice within each animal type) is less than that for cattle. Annual livestock population data for these other livestock types, except horses and goats, as well as feedlot placement information were obtained for all years from the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 1994a-b, 1995a,c, 1998a-b, 1999a,b,e,f, 2000a,b,e,f, 2001 a,b,e,f, 2002 a,b,e,f, 2003 a,b,e,f, 2004a,b,e-h, 2005a,d-h, 2006a,d-h). Horse population data were obtained from the FAOSTAT database (FAO 2006), because USDA does not estimate U.S. horse populations annually. Goat population data for 1992, 1997, and 2002 were obtained from the Census of Agriculture (USDA 2005i); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the *1992 and 1997 Census of Agriculture* (USDA 2005i). CH_4 emissions from sheep, goats, swine, and horses were estimated by using emission factors utilized in Crutzen et al. (1986, cited in IPCC/UNEP/OECD/IEA 1997). These emission factors are representative of typical animal sizes, feed intakes, and feed characteristics in developed countries. The methodology is the same as that recommended by IPCC (IPCC/UNEP/OECD/IEA 1997, IPCC 2000).

See Annex 3.9 for more detailed information on the methodology and data used to calculate CH_4 emissions from enteric fermentation.

Uncertainty

Quantitative uncertainty of this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, Monte Carlo Stochastic Simulation technique as described in ICF (2003). These estimates were developed for the 2001 inventory estimates. No significant changes occurred in the method of data collection, data estimation methodology, or other factors that influence the uncertainty ranges around the 2005 activity data and emission factor input variables. Consequently, these uncertainty estimates were directly applied to the 2005 emission estimates.

A total of 185 primary input variables (177 for cattle and 8 for non-cattle) were identified as key input variables for uncertainty analysis. The normal distribution was assumed for almost all activity- and emission factor-related input variables. Triangular distributions were assigned to three input variables (specifically, cow-birth ratios for the three most recent years included in the 2001 model run). For some key input variables, the uncertainty ranges around their estimates (used for inventory estimation) were collected from published documents and other public sources. In addition, both endogenous and exogenous correlations between selected primary input variables were modeled. The exogenous correlation coefficients between the probability distributions of selected activity-related variables were developed as educated estimates.

The uncertainty ranges associated with the activity-related input variables were plus or minus 10 percent or lower. However, for many emission factor-related input variables, the lower- and/or the upper-bound uncertainty estimates were over 20 percent. The results of the quantitative uncertainty analysis (Table 6-5) indicate that, on average, the emission estimate range of this source is approximately 99.8 to 132.3 Tg CO_2 Eq., within the range of approximately 11 percent below and 18 percent above the actual 2005 emission estimate of 112.1 Tg CO_2 Eq. Among the individual sub-source categories, beef cattle account for the largest amount of CH_4 emissions as well as the largest degree of uncertainty in the inventory emission estimates. Consequently, the cattle sub-source categories together contribute to the largest degree of uncertainty in the inventory estimates of CH_4 emissions from livestock enteric fermentation. Among non-cattle, horses account for the largest degree of uncertainty in the inventory emission estimates.

Table 6-5: Quantitative Uncertainty Estimates for CH_4 Emissions from Enteric Fermentation (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a, b] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Enteric Fermentation	CH_4	112.1	99.8	132.3	-11%	+18%

[a] Range of emissions estimates predicted by Monte Carlo Stochastic Simulation for a 95% confidence interval.
[b] Note that the relative uncertainty range was estimated with respect to the 2001 emission estimates and applied to 2005 estimates.

QA/QC and Verification

In order to ensure the quality of the emission estimates from enteric fermentation, the IPCC Tier 1 and Tier 2 Quality Assurance/Quality Control (QA/QC) procedures were implemented consistent with the U.S. QA/QC plan. Tier 2 QA procedures included independent peer review of emission estimates. Particular emphasis was placed this year on cattle population and growth data, and on evaluating the effects of data updates as described in the recalculations discussion below.

Recalculations Discussion

While there were no changes in the methodologies used for estimating CH_4 emissions from enteric fermentation, emissions were revised slightly due to changes in data. USDA published revised population estimates which affected historical emissions estimated for swine, sheep, goats, and poultry. Recent historical emission estimates also changed for certain beef and dairy populations as a result USDA inputs and the calving rate described below.

The emission factor for bulls has also changed according to IPCC (2006). Previously, the emission factor for bulls was 100 kg CH_4/head/yr, which in the 2006 IPCC Guidelines was changed to 53 kg CH_4/head/yr. This change in the emission factor resulted in an annual 47 percent decrease in emissions from bulls.

Several changes to previously reported emissions occurred due to revisions to population data and a change to the emissions factor for bulls. Year 2002 total (dairy and beef) cattle CH_4 emissions decreased by 2 percent. For 2004, beef cattle CH_4 emissions decreased 2.6 percent while dairy cattle emissions remained relatively constant. The majority of the change in emissions from beef cattle is a result of the change in emission factor for bulls. The decreased emission factor in bull emissions from 1990 through 2005 resulted in a decrease in CH_4 emissions for each of those years. In 2004, this change lowered emissions by 100 Gg (2.0 percent of total enteric fermentation emissions from all animals). Recent historical emission estimates for swine changed (by less than one half of one percent of respective 2004 emissions) as a result of the USDA revisions described above.

Planned Improvements

Continued research and regular updates are necessary to maintain a current model of cattle diet characterization, feedlot placement data, rates of weight gain and calving, among other data inputs. While EPA has no plans for methodological changes in the modeling framework, the opportunity exists to continue to refine the model's results through identifying and improving individual data inputs. Research is currently underway to differentiate emissions from "dry" and lactating cows within the model. This improvement to the model would improve inventory estimates by taking into account the milk production for lactating cows. Other research is currently underway to identify updates of this nature.

6.2. Manure Management (IPCC Source Category 4B)

The management of livestock manure can produce anthropogenic CH_4 and N_2O emissions. CH_4 is produced by the anaerobic decomposition of manure. N_2O is produced as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine.[1]

When livestock or poultry manure are stored or treated in systems that promote anaerobic conditions (e.g., as a liquid/slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4. Ambient temperature, moisture, and manure storage or residency time affect the amount of CH_4 produced because they influence the growth of the bacteria responsible for CH_4 formation. For non-liquid-based manure systems, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production. Manure composition, which varies by animal diet, growth rate, and type, including the animal's digestive system, also affects the amount of CH_4 produced. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. However, some higher energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

The production of N_2O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system. For N_2O emissions to occur, the manure must first be handled aerobically where ammonia or organic nitrogen is converted to nitrates and nitrites (nitrification), and then handled anaerobically where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O and nitric oxide (NO) (denitrification) (Groffman et al. 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions, but that also contain pockets of anaerobic conditions due to saturation. A very small portion of the total nitrogen excreted is expected to convert to N_2O in the waste management system.

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[1] Emissions from livestock manure and urine deposited on pasture, range, or paddock lands, indirect emissions from volatile nitrogen losses that occur primarily in the forms of ammonia and NO_x, and emissions from manure and urine spread onto fields either directly as "daily spread" or after it is removed from manure management systems (e.g., lagoon, pit, etc.) are accounted and discussed in the Agricultural Soil Management source category within the Agriculture sector.

Estimates of CH_4 emissions in 2005 were 41.3 Tg CO_2 Eq. (1,966 Gg), 34 percent higher than in 1990. Emissions increased on average by 0.7 Tg CO_2 Eq. (2 percent) annually over this period. The majority of this increase was from swine and dairy cow manure, where emissions increased 37 and 50 percent, respectively. Although the majority of manure in the United States is handled as a solid, producing little CH_4, the general trend in manure management, particularly for dairy and swine (which are both shifting towards larger facilities), is one of increasing use of liquid systems. Also, new regulations limiting the application of manure nutrients have shifted manure management practices at smaller dairies from daily spread to manure managed and stored on site. Although national dairy animal populations have been generally decreasing, some states have seen increases in their dairy populations as the industry becomes more concentrated in certain areas of the country. These areas of concentration, such as California, New Mexico, and Idaho, tend to utilize more liquid-based systems to manage (flush or scrape) and store manure. Thus the shift toward larger facilities is translated into an increasing use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. This shift was accounted for by incorporating state-specific weighted CH_4 conversion factor (MCF) values in combination with the 1992, 1997, and 2002 farm-size distribution data reported in the *Census of Agriculture* (USDA 2005e). From 2004 to 2005, there was a 4 percent increase in CH_4 emissions, due to minor shifts in the animal populations and the resultant effects on manure management system allocations.

In 2005, total N_2O emissions were estimated to be 9.5 Tg CO_2 Eq. (31 Gg); in 1990, emissions were 8.6 Tg CO_2 Eq. (28 Gg). Emissions increased on average by 0.06 Tg CO_2 Eq. (0.7 percent) annually over this period, driven by beef cattle. The 10 percent increase in N_2O emissions from 1990 to 2005 can be partially attributed to a shift in the poultry industry away from the use of liquid manure management systems in favor of litter-based systems and high-rise houses. In addition, there was an overall increase in the population of poultry and swine from 1990 to 2005, although swine populations periodically declined slightly throughout the time series. N_2O emissions showed a 0.9 percent increase from 2004 through 2005, due to minor shifts in animal populations.

The population of beef cattle in feedlots increased over the period of 1990 to 2005, resulting in increased N_2O emissions from this sub-category of cattle. N_2O emissions from dairy cattle increased slightly over the period 1990 through 2005, a net result of different emission trends for dairy cows and dairy heifers. Although dairy cow populations decreased overall for the period 1990 through 2005, the population of dairy cows increased at dairies that manage and store manure on-site (as opposed to using pasture, range, or paddock or daily spread systems). The shift at dairies to more liquid manure management systems at large operations resulted in lower N_2O emissions for dairy cows. This trend differed from the increasing dairy heifer N_2O emissions from dairy heifers, whose populations were increasingly managed in drylot systems.

Table 6-6and Table 1-6-7 provide estimates of CH_4 and N_2O emissions from manure management by animal category.

Table 6-6: CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq.)

Gas/Animal Type	**1990**	**1995**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
CH_4	**30.9**	**35.1**	**38.7**	**40.1**	**41.1**	**40.5**	**39.7**	**41.3**
Dairy Cattle	11.9	13.3	15.7	16.6	17.2	17.6	17.1	17.9
Beef Cattle	2.5	2.6	2.4	2.5	2.4	2.4	2.3	2.3
Swine	13.1	16.0	17.4	17.8	18.3	17.2	17.1	17.9
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	2.7	2.7	2.6	2.7	2.7	2.7	2.6	2.6
Horses	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.5
N_2O	**8.6**	**9.0**	**9.6**	**9.8**	**9.7**	**9.3**	**9.4**	**9.5**
Dairy Cattle	2.4	2.4	2.5	2.5	2.5	2.5	2.5	2.5
Beef Cattle	4.9	5.3	5.9	6.1	6.0	5.6	5.7	5.8
Swine	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sheep	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Goats	+	+	+	+	+	+	+	+
Poultry	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Horses	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Total	**39.5**	**44.1**	**48.3**	**50.0**	**50.8**	**49.8**	**49.2**	**50.8**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 1-6-7: CH_4 and N_2O Emissions from Manure Management (Gg)

Gas/Animal Type	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**1,471**	**1,673**	**1,844**	**1,911**	**1,959**	**1,928**	**1,892**	**1,966**
Dairy Cattle	568	634	748	789	818	839	814	851
Beef Cattle	120	122	114	117	114	113	110	111
Swine	623	762	830	849	873	821	815	852
Sheep	7	5	4	4	4	4	4	4
Goats	1	1	1	1	1	1	1	1
Poultry	131	128	125	129	127	127	126	125
Horses	22	21	22	22	22	22	22	22
N_2O	**28**	**29**	**31**	**32**	**31**	**30**	**30**	**31**
Dairy Cattle	8	8	8	8	8	8	8	8
Beef Cattle	16	17	19	20	19	18	19	19
Swine	2	2	2	1	2	2	2	2
Sheep	0	0	0	0	0	0	0	0
Goats	0	0	0	0	0	0	0	0
Poultry	1	1	1	1	1	1	1	1
Horses	1	1	1	1	1	1	1	1

+ Does not exceed 0.5 Gg.
Note: Totals may not sum due to independent rounding.

Methodology

The methodologies presented in IPCC (2006) form the basis of the CH_4 and N_2O emission estimates for each animal type. The calculation of emissions requires the following information:

- Animal population data (by animal type and state);
- Amount of nitrogen produced (excretion rate by animal type times animal population);
- Amount of volatile solids produced (excretion rate by animal type times animal population);
- CH_4 producing potential of the volatile solids (by animal type);
- Extent to which the CH_4 producing potential is realized for each type of manure management system (by state and manure management system, including the impacts of any biogas collection efforts);
- Portion of manure managed in each manure management system (by state and animal type); and
- Portion of manure deposited on pasture, range, or paddock or used in daily spread systems.

This section presents a summary of the methodologies used to estimate CH_4 and N_2O emissions from manure management for this inventory. See Annex 3.10 for more detailed information on the methodology and data used to calculate CH_4 and N_2O emissions from manure management.

Both CH_4 and N_2O emissions were estimated by first determining activity data, including animal population, waste characteristics, and manure management system usage. For swine and dairy cattle, manure management system usage was determined for different farm size categories using data from USDA (USDA 1996b, 1998c, 2000b) and EPA (ERG 2000a, EPA 2002a, 2002b). For beef cattle and poultry, manure management system usage data were not tied to farm size but were based on other data sources (ERG 2000a, USDA 2000c, UEP 1999). For other animal types, manure management system usage was based on previous estimates (EPA 1992).

MCFs and N_2O emission factors were determined for all manure management systems. MCFs for dry systems were set equal to default IPCC factors based on each state's climate for each year (IPCC 2006). MCFs for liquid/slurry, anaerobic lagoon, and deep pit systems were calculated based on the forecast performance of biological systems relative to temperature changes as predicted in the van't Hoff-Arrhenius equation. The MCF calculations model the average monthly ambient temperature, a minimum system temperature, the carryover of volatile solids in the system from month to month due to long storage times exhibited by anaerobic lagoon systems, and a factor to account for management and design practices that result in the loss of volatile solids from lagoon systems. N_2O emission factors for all systems were set equal to default IPCC factors (IPCC 2006).

CH_4 emissions were estimated using the volatile solids (VS) production for all livestock. For most cattle groups, regional animal-specific VS production rates that are related to the diet of the animal for each year of the inventory were used (Pederson and Pape 2006). For all other animal groups, VS production was calculated using a national average VS production rate from the *Agricultural Waste Management Field Handbook* (USDA 1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. The resulting VS for each animal group were then multiplied by the maximum CH_4 producing capacity of the waste (B_o) and the state-specific MCFs.

The maximum CH_4 producing capacity of the VS, or B_o, was determined based on data collected in a literature review (ERG 2000b). B_o data were collected for each animal type for which emissions were estimated.

Anaerobic digester reductions are estimated based on data from the EPA AgSTAR program, including information presented in the *AgSTAR Digest* (EPA 2000, 2003b, 2006). A destruction efficiency of 99 percent was applied to CH_4 recovered to estimate CH_4 emissions from digesters. The value for efficiency was selected based on the range of efficiencies (98 to 100 percent) recommended for flares in EPA's "AP-42 Compilation of Air Pollutant Emission Factors, Chapter 2.4," efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in LMOP.

Nitrogen excretion rate data from the USDA *Agricultural Waste Management Field Handbook* (USDA 1996a) were used for all livestock except sheep, goats, and horses. Data from the American Society of Agricultural Engineers (ASAE 1999) were used for these animal types. VS excretion rate data from USDA (1996a) were used for swine, poultry, bulls, and calves not on feed.

N_2O emissions were estimated by determining total Kjeldahl nitrogen (TKN)[2] production for all livestock wastes using a national average nitrogen excretion rate for each animal group from USDA (1996a), which was then multiplied by the average weight of the animal and the state-specific animal population. State-specific weighted N_2O emission factors specific to the type of manure management system were then applied to total nitrogen production to estimate N_2O emissions.

Uncertainty

An analysis was conducted for the manure management emission estimates presented in EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2001* (EPA 2003a, ERG 2003) to determine the uncertainty associated with estimating CH_4 and N_2O emissions from livestock manure management. Because no substantial modifications were made to the inventory methodology since the development of these estimates, it is expected that this analysis is applicable to the uncertainty associated with the current manure management emission estimates.

The quantitative uncertainty analysis for this source category was performed through the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The uncertainty analysis was developed based on the methods used to estimate CH_4 and N_2O emissions from manure management systems. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and state. The equations for each animal group contained four to five variables around which the uncertainty analysis was performed for each state.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 1-6-8. Manure management CH_4

[2] Total Kjeldahl nitrogen is a measure of organically bound nitrogen and ammonia nitrogen.

emissions in 2005 were estimated to be between 33.8 and 49.5 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 18 percent below to 20 percent above the actual 2005 emission estimate of 41.3 Tg CO_2 Eq. At the 95 percent confidence level, N_2O emissions were estimated to be between 8.0 and 11.8 Tg CO_2 Eq. (or approximately 16 percent below and 24 percent above the actual 2005 emission estimate of 9.5 Tg CO_2 Eq.).

Table 1-6-8: Tier 2 Quantitative Uncertainty Estimates for CH_4 and N_2O Emissions from Manure Management (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Manure Management	CH_4	41.3	33.8	49.5	-18%	+20%
Manure Management	N_2O	9.5	8.0	11.8	-16%	+24%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

Tier 1 and Tier 2 QA/QC activities were conducted consistent with the U.S. QA/QC plan. Tier 2 activities focused on comparing estimates for the 2004 and 2005 Inventories for N_2O emissions from managed systems and CH_4 emissions from livestock manure. All errors identified were corrected. Order of magnitude checks were also conducted, and corrections made where needed. Manure nitrogen data were checked by comparing state-level data with bottom up estimates derived at the county level and summed to the state level. Similarly, a comparison was made by animal and waste management system type for the full time series, between national level estimates for nitrogen excreted and the sum of county estimates for the full time series.

Recalculations Discussion

A few changes have been incorporated into the overall methodology for the manure management emission estimates. State temperatures are now calculated using data from every county in the state. The previous methodology linked the temperature data to a list of counties/climate divisions that were determined using a weather station list from the National Climatic Data Center (NCDC). The list of weather stations, however, did not include a match of county to climate division for all U.S. counties. The new methodology for utilizing the temperature data for the contiguous United States is to link the temperature data by climate division to a complete list of U.S. counties/climate divisions (NOAA 2005). Although this change in methodology provides a more accurate calculation of state temperatures, it has little effect on the final temperature calculations, MCFs, or emissions estimates.

Another major change in methodology was using climate-specific MCFs for dry manure management systems. In previous inventories, a "temperate" climate zone was assumed for all U.S. states and years of the inventory, and the temperate MCFs for all dry manure management systems were used in methane emission calculations. A climate classification (cool, temperate, or warm) was assigned to each state and year using the average state temperatures. New climate-specific MCFs were incorporated into the current inventory for the following manure management systems: pasture/range/paddock, daily spread, solid storage, dry lot, burned for fuel, cattle deep bedding (<1 month and >1 month), composting – intensive windrow, and composting – passive windrow. The change in status for some states from temperate to cool climates and MCFs caused the most significant changes in methane emissions for animal groups that most rely on pasture/range/paddock waste management systems (i.e., beef cattle, sheep, horses, and goats), which showed decreased CH_4 emissions for all years in the current inventory compared to the previous inventory.

The percentage of dairy cattle, swine, and sheep on each type of manure management system was also updated for the 2005 inventory, based on farm size data from the 2002 USDA Census of Agriculture. Liquid-based systems are in increasing use for swine and dairy manure, due to the increasing farm size for these animals. Sheep continue to be managed using dry manure management systems. These manure management system updates decreased N_2O

estimates and increased CH_4 estimates for dairy cattle and increased N_2O and CH_4 estimates for swine in the current inventory.

Changes were also made to the current calculations involving animal population data. Animal population data were updated to reflect the final estimates reports from USDA NASS, and 2002 USDA Census of Agriculture data (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-d, 2006a-e). The population data in the most recent final estimates reflect some adjustments due to USDA NASS review. For horses, state-level populations were estimated using the national FAO population data (FAO 2006) and the state distributions from the 1992, 1997, and 2002 Census of Agriculture (USDA 2005e).

For the current inventory, new VS production and nitrogen excretion rates were calculated for poultry hens and pullets, based on 1990 to 2004 population and VS data and nitrogen excretion data. This change was incorporated because USDA now reports a combined hen and pullet population, therefore weighted average rates for the combined population were developed.

With these recalculations, CH_4 emission estimates from manure management systems are slightly higher than reported in the previous inventory for the years 1999 through 2004 and slightly lower for 1990 through 1998. On average, annual emissions estimates are less than those of the previous inventory by less than one percent.

N_2O emission estimates from manure management systems have decreased for all years of the current inventory compared to the previous inventory, by 47 percent on average, due to the use of updated emission factors published by IPCC (2006).

Planned Improvements

Although an effort was made to introduce the variability in VS production due to differences in diet for beef and dairy cows, heifers, and steer, further research is needed to confirm and track diet changes over time. A methodology to assess variability in swine VS production would be useful in future inventory estimates.

Research will be initiated into the estimation and validation of the maximum CH_4-producing capacity of animal manure (B_o), for the purpose of obtaining more accurate data to develop emission estimates.

The American Society of Agricultural Engineers proposed new standards for manure production characteristics in 2004 and finalized them in 2005. These data will be investigated and evaluated for incorporation into future estimates.

The methodology to calculate MCFs for liquid systems will be examined to determine how to account for a maximum temperature in the liquid systems. It will also be evaluated whether the lower bound estimate of temperature established for lagoons and other liquid systems should be revised for use with this methodology. Additionally, available research will be investigated to develop a relationship between ambient air temperature and temperature in liquid waste management systems in order to improve that relationship in the MCF methodology.

The development of the National Ammonia Emissions Inventory for the United States (EPA 2004) used similar data sources to the current estimates of emissions from manure management, and through the course of development of the ammonia inventory, updated waste management distribution data were identified. Future inventory estimates will incorporate these updated data.

The estimation of indirect N_2O emissions associated with manure management (e.g., ammonia NO_x) is currently included in the Agricultural Soil Management source category. Based on IPCC (2006), a methodology to estimate these indirect N_2O emissions separately and include them in the Manure Management source category will be evaluated for future inventories.

The IPCC provides a suggested MCF for poultry waste management operations of 1.5 percent. Additional study is needed in this area to determine if poultry high-rise houses promote sufficient aerobic conditions to warrant a lower MCF.

A minor error was identified in the MCF calculations, which used a value of 303.17 K instead of 303.15 K when calculating the f factor. This error will be corrected in future inventory estimates. This error has little impact overall on the CH_4 emission estimates. The calculated MCFs are expected to increase up to 0.1 percent, and the overall CH_4 emissions are expected to increase by up to 0.05 percent.

6.3. Rice Cultivation (IPCC Source Category 4C)

Most of the world's rice, and all rice in the United States, is grown on flooded fields. When fields are flooded, aerobic decomposition of organic material gradually depletes most of the oxygen present in the soil, causing anaerobic soil conditions. Once the environment becomes anaerobic, CH_4 is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria. As much as 60 to 90 percent of the CH_4 produced is oxidized by aerobic methanotrophic bacteria in the soil (some oxygen remains at the interfaces of soil and water, and soil and root system) (Holzapfel-Pschorn et al. 1985, Sass et al. 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining un-oxidized CH_4 is transported from the submerged soil to the atmosphere primarily by diffusive transport through the rice plants. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is one of the most important factors affecting CH_4 emissions. Upland rice fields are not flooded, and therefore are not believed to produce CH_4. In deepwater rice fields (i.e., fields with flooding depths greater than one meter), the lower stems and roots of the rice plants are dead, so the primary CH_4 transport pathway to the atmosphere is blocked. The quantities of CH_4 released from deepwater fields, therefore, are believed to be significantly less than the quantities released from areas with shallower flooding depths. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils. All rice in the United States is grown under continuously flooded conditions; none is grown under deepwater conditions. Mid-season drainage does not occur except by accident (e.g., due to levee breach).

Other factors that influence CH_4 emissions from flooded rice fields include fertilization practices (especially the use of organic fertilizers), soil temperature, soil type, rice variety, and cultivation practices (e.g., tillage, seeding, and weeding practices). The factors that determine the amount of organic material available to decompose (i.e., organic fertilizer use, soil type, rice variety,[3] and cultivation practices) are the most important variables influencing the amount of CH_4 emitted over the growing season; the total amount of CH_4 released depends primarily on the amount of organic substrate available. Soil temperature is known to be an important factor regulating the activity of methanogenic bacteria, and therefore the rate of CH_4 production. However, although temperature controls the amount of time it takes to convert a given amount of organic material to CH_4, that time is short relative to a growing season, so the dependence of total emissions over an entire growing season on soil temperature is weak. The application of synthetic fertilizers has also been found to influence CH_4 emissions; in particular, both nitrate and sulfate fertilizers (e.g., ammonium nitrate and ammonium sulfate) appear to inhibit CH_4 formation.

Rice is cultivated in eight states: Arkansas, California, Florida, Louisiana, Mississippi, Missouri, Oklahoma, and Texas.[4] Soil types, rice varieties, and cultivation practices for rice vary from state to state, and even from farm to farm. However, most rice farmers apply organic fertilizers in the form of residue from the previous rice crop, which is left standing, disked, or rolled into the fields. Most farmers also apply synthetic fertilizer to their fields, usually urea. Nitrate and sulfate fertilizers are not commonly used in rice cultivation in the United States. In addition, the climatic conditions of Arkansas, southwest Louisiana, Texas, and Florida allow for a second, or ratoon, rice crop.

[3] The roots of rice plants shed organic material, which is referred to as "root exudate." The amount of root exudate produced by a rice plant over a growing season varies among rice varieties.

[4] Additionally, a very small amount of rice is grown on about 20 acres in South Carolina; however, this amount was determined to be too insignificant to warrant inclusion in national emissions estimates.

CH_4 emissions from ratoon crops have been found to be considerably higher than those from the primary crop. This second rice crop is produced from regrowth of the stubble after the first crop has been harvested. Because the first crop's stubble is left behind in ratooned fields, and there is no time delay between cropping seasons (which would allow the stubble to decay aerobically), the amount of organic material that is available for anaerobic decomposition is considerably higher than with the first (i.e., primary) crop.

Rice cultivation is a small source of CH_4 in the United States (Table 6-9 and Table 6-10). In 2005, CH_4 emissions from rice cultivation were 6.9 Tg CO_2 Eq. (328 Gg). Although annual emissions fluctuated unevenly between the years 1990 and 2005, ranging from an annual decrease of 11 percent to an annual increase of 17 percent, there was an overall decrease of 3 percent over the fifteen-year period, due to an overall decrease in primary crop area.[5] The factors that affect the rice acreage in any year vary from state to state, although the price of rice relative to competing crops is the primary controlling variable in most states.

Table 6-9: CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq.)

State	1990	1995	2000	2001	2002	2003	2004	2005
Primary	**5.1**	**5.6**	**5.5**	**5.9**	**5.7**	**5.4**	**6.0**	**6.0**
Arkansas	2.1	2.4	2.5	2.9	2.7	2.6	2.8	2.9
California	0.7	0.8	1.0	0.8	0.9	0.9	1.1	0.9
Florida	+	0.0	+	+	+	+	+	+
Louisiana	1.0	1.0	0.9	1.0	1.0	0.8	1.0	0.9
Mississippi	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.5
Missouri	0.1	0.2	0.3	0.4	0.3	0.3	0.3	0.4
Oklahoma	+	0.0	+	+	+	+	+	+
Texas	0.6	0.6	0.4	0.4	0.4	0.3	0.4	0.4
Ratoon	**2.1**	**2.1**	**2.0**	**1.7**	**1.1**	**1.5**	**1.6**	**0.9**
Arkansas	+	0.0	+	+	+	+	+	+
Florida	+	0.1	0.1	+	+	+	+	+
Louisiana	1.1	1.1	1.3	1.1	0.5	1.0	1.1	0.5
Texas	0.9	0.8	0.7	0.6	0.5	0.5	0.5	0.4
Total	**7.1**	**7.6**	**7.5**	**7.6**	**6.8**	**6.9**	**7.6**	**6.9**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-10: CH_4 Emissions from Rice Cultivation (Gg)

State	1990	1995	2000	2001	2002	2003	2004	2005
Primary	**241**	**265**	**260**	**283**	**274**	**255**	**283**	**287**
Arkansas	102	114	120	138	128	124	132	139
California	34	40	47	40	45	43	50	45
Florida	1	2	2	1	1	+	1	1
Louisiana	46	48	41	46	45	38	45	45
Mississippi	21	24	19	22	22	20	20	22
Missouri	7	10	14	18	15	15	17	18
Oklahoma	+	+	+	+	+	+	+	+
Texas	30	27	18	18	18	15	19	17
Ratoon	**98**	**98**	**97**	**81**	**52**	**73**	**77**	**41**
Arkansas	+	+	+	+	+	+	+	1
Florida	2	4	2	2	2	2	2	2
Louisiana	52	54	61	52	25	50	50	22

[5] The 11 percent decrease occurred between 1992 and 1993 and 2001 and 2002; the 17 percent increase happened between 1993 and 1994.

Texas	45	40	34	27	24	22	24	17
Total	**339**	**363**	**357**	**364**	**325**	**328**	**360**	**328**

+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The IPCC/UNEP/OECD/IEA (1997) recommends using harvested rice areas and area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to estimate annual CH_4 emissions from rice cultivation. This Inventory uses the recommended methodology and employs U.S.-specific emission factors derived from rice field measurements. Seasonal emissions have been found to be much higher for ratooned crops than for primary crops, so emissions from ratooned and primary areas are estimated separately using emission factors that are representative of the particular growing season. This approach is consistent with IPCC *Good Practice Guidance* (IPCC 2000).

The harvested rice areas for the primary and ratoon crops in each state are presented in Table 6-11. Primary crop areas for 1990 through 2005 for all states except Florida and Oklahoma were taken from U.S. Department of Agriculture's *Field Crops Final Estimates 1987-1992* (USDA 1994), *Field Crops Final Estimates 1992-1997* (USDA 1998), *Field Crops Final Estimates 1997-2002* (USDA 2003), and *Crop Production Summary* (USDA 2005, 2006). Harvested rice areas in Florida, which are not reported by USDA, were obtained from: Tom Schueneman (1999b, 1999c, 2000, 2001a) and Arthur Kirstein (2003, 2006), Florida agricultural extension agents; Dr. Chris Deren (2002) of the Everglades Research and Education Centre at the University of Florida; and Gaston Cantens (2004, 2005), Vice President of Corporate Relations of the Florida Crystals Company. Harvested rice area in Florida for 2005 was unavailable and set equal to the 2004 figure (Kirstein 2006, Cantens 2005). Harvested rice areas for Oklahoma, which also are not reported by USDA, were obtained from Danny Lee of the Oklahoma Farm Services Agency (2003, 2004, 2005, 2006). Acreages for the ratoon crops were derived from conversations with the agricultural extension agents in each state. In Arkansas, ratooning occurred only in 1998, 1999, and 2005, when the ratooned area was less than 1 percent of the primary area (Slaton 1999, 2000, 2001a; Wilson 2002, 2003, 2004, 2005, 2006). In Florida, the ratooned area was 50 percent of the primary area from 1990 to 1998 (Schueneman 1999a), about 65 percent of the primary area in 1999 (Schueneman 2000), around 41 percent of the primary area in 2000 (Schueneman 2001a), about 60 percent of the primary area in 2001 (Deren 2002), about 54 percent of the primary area in 2002 (Kirstein 2003), about 100 percent of the primary area in 2003 (Kirstein 2004), and about 77 percent of the primary area in 2004 (Cantens 2005). Ratooned area for 2005 was set equal to 2004, since no new data were available. In Louisiana, the percentage of the primary area that was ratooned was constant at 30 percent over the 1990 to 1999 period, increased to approximately 40 percent in 2000, returned to 30 percent in 2001, dropped to 15 percent in 2002, rose to 35 percent in 2003, returned to 30 percent in 2004, and dropped to 13 percent in 2005 (Linscombe 1999, 2001a, 2002, 2003, 2004, 2005, 2006; Bollich 2000). In Texas, the percentage of the primary area that was ratooned was constant at 40 percent over the 1990 to 1999 period, increased to 50 percent in 2000 due to an early primary crop, and then decreased to 40 percent in 2001, 37 percent in 2002, 38 percent in 2003, 35 percent in 2004, and 27 percent in 2005 (Klosterboer 1999, 2000, 2001a, 2002, 2003; Stansel 2004, 2005; Texas Agricultural Experiment Station 2006). California, Mississippi, Missouri, and Oklahoma have not ratooned rice over the period 1990-2005 (Guethle 1999, 2000, 2001a, 2002, 2003, 2004, 2005, 2006; Lee 2003, 2004, 2005, 2006; Mutters 2002, 2003, 2004, 2005; Street 1999, 2000, 2001a, 2002, 2003; Walker 2005).

Table 6-11: Rice Areas Harvested (Hectares)

State/Crop	1990	1995	2000	2001	2002	2003	2004	2005
Arkansas								
Primary	485,633	542,291	570,619	656,010	608,256	588,830	629,300	661,675
Ratoon*	0	0	0	0	0	0	0	662
California	159,854	188,183	221,773	190,611	213,679	205,180	238,770	212,869
Florida								
Primary	4,978	9,713	7,801	4,562	5,077	2,369	3,755	3,755
Ratoon	2,489	4,856	3,193	2,752	2,734	2,369	2,899	2,899
Louisiana								
Primary	220,558	230,676	194,253	220,963	216,512	182,113	215,702	212,465

Ratoon	66,168	69,203	77,701	66,289	32,477	63,739	64,711	27,620
Mississippi	101,174	116,552	88,223	102,388	102,388	94,699	94,699	106,435
Missouri	32,376	45,326	68,393	83,772	73,654	69,203	78,915	86,605
Oklahoma	617	364	283	265	274	53	158	271
Texas								
Primary	142,857	128,693	86,605	87,414	83,367	72,845	88,223	81,344
Ratoon	57,143	51,477	43,302	34,966	30,846	27,681	30,878	21,963
Total Primary	**1,148,047**	**1,261,796**	**1,237,951**	**1,345,984**	**1,303,206**	**1,215,291**	**1,349,523**	**1,365,418**
Total Ratoon	**125,799**	**125,536**	**124,197**	**104,006**	**66,056**	**93,790**	**98,488**	**53,144**
Total	**1,273,847**	**1,387,333**	**1,362,148**	**1,449,991**	**1,369,262**	**1,309,081**	**1,448,011**	**1,418,562**

* Arkansas ratooning occurred only in 1998, 1999, and 2005.
Note: Totals may not sum due to independent rounding.

To determine what seasonal CH_4 emission factors should be used for the primary and ratoon crops, CH_4 flux information from rice field measurements in the United States was collected. Experiments which involved atypical or nonrepresentative management practices (e.g., the application of nitrate or sulfate fertilizers, or other substances believed to suppress CH_4 formation), as well as experiments in which measurements were not made over an entire flooding season or floodwaters were drained mid-season, were excluded from the analysis. The remaining experimental results[6] were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with added synthetic and organic fertilizer (Bossio et al. 1999; Cicerone et al. 1992; Sass et al. 1991a, 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with added synthetic fertilizer (Lindau and Bollich 1993, Lindau et al. 1995) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 210 kg CH_4/hectare-season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/hectare-season.

Uncertainty

The largest uncertainty in the calculation of CH_4 emissions from rice cultivation is associated with the emission factors. Seasonal emissions, derived from field measurements in the United States, vary by more than one order of magnitude. This inherent variability is due to differences in cultivation practices, in particular, fertilizer type, amount, and mode of application; differences in cultivar type; and differences in soil and climatic conditions. A portion of this variability is accounted for by separating primary from ratooned areas. However, even within a cropping season or a given management regime, measured emissions may vary significantly. Of the experiments used to derive the emission factors applied here, primary emissions ranged from 22 to 479 kg CH_4/hectare-season and ratoon emissions ranged from 481 to 1,490 kg CH_4/hectare-season. The uncertainty distributions around the primary and ratoon emission factors were derived using the distributions of the relevant primary or ratoon emission factors available in the literature and described above. Variability about the rice emission factor means was not normally distributed for either primary or ratooned crops, but rather skewed, with a tail trailing to the right of the mean. A lognormal statistical distribution was, therefore, applied in the Tier 2 Monte Carlo analysis.

Other sources of uncertainty include the primary rice-cropped area for each state, percent of rice-cropped area that is rationed, and the extent to which flooding outside of the normal rice season is practiced. Expert judgment was used to estimate the uncertainty associated with primary rice-cropped area for each state at 1 to 5 percent, and a normal distribution was assumed. Uncertainties were applied to ratooned area by state, based on the level of reporting performed by the state. No uncertainties were calculated for the practice of flooding outside of the normal rice season because CH_4 flux measurements have not been undertaken over a sufficient geographic range or under a

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[6] In some of these remaining experiments, measurements from individual plots were excluded from the analysis because of the aforementioned reasons. In addition, one measurement from the ratooned fields (i.e., the flux of 2.041 g/m^2/day in Lindau and Bollich 1993) was excluded, because this emission rate is unusually high compared to other flux measurements in the United States, as well as in Europe and Asia (IPCC/UNEP/OECD/IEA 1997).

broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 6-12. Rice cultivation CH_4 emissions in 2005 were estimated to be between 2.1 and 18.6 Tg CO_2 Eq. at a 95 percent confidence level, which indicates a range of 70 percent below to 170 percent above the actual 2005 emission estimate of 6.9 Tg CO_2 Eq.

Table 6-12: Tier 2 Quantitative Uncertainty Estimates for CH_4 Emissions from Rice Cultivation (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Rice Cultivation	CH_4	6.9	2.1	18.6	-70%	+170%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for rice cultivation was developed and implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and cropping seasons to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

An error in the spreadsheets used to calculate emissions estimates was found during the development of the current inventory and corrected, resulting in a 0.06 percent decrease in the 2004 emission estimates.

6.4. Agricultural Soil Management (IPCC Source Category 4D)

Nitrous oxide is produced naturally in soils through the microbial processes of nitrification and denitrification.[7] A number of agricultural activities increase mineral nitrogen (N) availability in soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted. These activities increase soil mineral N either directly or indirectly (see Figure 6-2). Direct increases occur through a variety of management practices that add or lead to greater release of mineral N in the soil, including: fertilization; application of managed livestock manure and other organic materials such as sewage sludge; deposition of manure on soils by domesticated animals in pastures, rangelands, and paddocks (PRP) (i.e., by grazing animals and other animals whose manure is not managed); production of N-fixing crops and forages; retention of crop residues; and cultivation of organic soils (i.e., soils with a high organic matter content, otherwise known as histosols).[8] Other agricultural soil management activities, including irrigation, drainage, tillage practices, and fallowing of land, can influence N mineralization in soils and thereby affect direct emissions. Mineral N is also made available in soils through decomposition of soil

[7] Nitrification and denitrification are driven by the activity of microorganisms in soils. Nitrification is the aerobic microbial oxidation of ammonium (NH_4) to nitrate (NO_3), and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate product in the reaction sequence of denitrification, which leaks from microbial cells into the soil and then into the atmosphere. Nitrous oxide is also produced during nitrification, although by a less well-understood mechanism (Nevison 2000).

[8] Drainage and cultivation of organic soils in former wetlands enhances mineralization of N-rich organic matter, thereby enhancing N_2O emissions from these soils.

organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere.[9] Indirect emissions of N_2O occur through two pathways: (1) volatilization and subsequent atmospheric deposition of applied N,[10] and (2) surface runoff and leaching of applied N into groundwater and surface water. Direct emissions from agricultural lands (i.e., croplands and grasslands) are included in this section, while direct emissions from forest lands and settlements are presented in the Land Use, Land-Use Change, and Forestry chapter. In contrast, indirect N_2O emissions from all sources (agriculture, forest lands, settlements, and managed manure) are reported in this chapter.

Figure 6-2: Agricultural Sources and Pathways of N that Result in N_2O Emissions

Agricultural soils produce the majority of N_2O emissions in the United States. Estimated emissions from this source in 2005 were 365.1 Tg CO_2 Eq. (1,178 Gg N_2O) (see Table 6-13 and Table 6-14). Annual agricultural soil management N_2O emissions fluctuated between 1990 and 2005, although overall emissions were 0.5 percent lower in 2005 than in 1990. Year-to-year fluctuations are largely a reflection of annual variation in weather patterns, synthetic fertilizer use, and crop production. On average, cropland accounted for approximately 75 percent of total direct emissions, while grassland accounted for approximately 25 percent.

Table 6-13: N_2O Emissions from Agricultural Soils (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Direct	**310.1**	**292.0**	**324.4**	**327.4**	**314.1**	**297.4**	**292.1**	**310.5**
Cropland	222.1	214.2	250.5	252.6	234.0	226.4	220.9	234.2
Grassland	88.0	77.8	73.9	74.8	80.1	71.0	71.3	76.4
Indirect (All Land-Use Types)	**56.8**	**61.4**	**52.4**	**61.6**	**52.0**	**52.8**	**46.6**	**54.6**
Cropland	27.2	27.2	25.0	26.1	22.5	25.7	20.1	26.2
Grassland	20.4	24.3	17.1	25.1	18.9	16.5	16.0	17.8
Managed Manure[a]	7.5	8.0	8.4	8.5	8.7	8.5	8.5	8.5
Forest Land	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	1.7	1.8	1.8	1.8	1.9	1.9	2.0	1.9
Total	**366.9**	**353.4**	**376.8**	**389.0**	**366.1**	**350.2**	**338.8**	**365.1**

+ Less than 0.05 Tg CO_2 Eq.
[a] Accounts for loss of manure N prior to soil application during transport, treatment, and storage, including both volatilization and leaching/runoff.

Table 6-14: N_2O Emissions from Agricultural Soils (Gg N_2O)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Direct	**1,000**	**942**	**1,046**	**1,056**	**1,013**	**959**	**942**	**1,002**
Cropland	716	691	808	815	755	730	712	755
Grassland	284	251	238	241	259	229	230	246
Indirect (All Land-Use Types)	**183**	**198**	**169**	**199**	**168**	**170**	**150**	**176**
Cropland	88	88	81	84	72	83	65	84
Grassland	66	78	55	81	61	53	52	57
Managed Manure[a]	24	26	27	27	28	28	27	28
Forest Land	+	+	+	+	+	+	+	+
Settlements	5	6	6	6	6	6	6	6
Total	**1,184**	**1,140**	**1,215**	**1,255**	**1,181**	**1,130**	**1,093**	**1,178**

[9] Asymbiotic N fixation is the fixation of atmospheric N_2 by bacteria living in soils that do not have a direct relationship with plants.

[10] These processes entail volatilization of applied N as ammonia (NH_3) and oxides of N (NO_x), transformation of these gases within the atmosphere (or upon deposition), and deposition of the N primarily in the form of particulate ammonium (NH_4), nitric acid (HNO_3), and NO_x.

+ Less than 0.5 Gg N_2O.
[a] Accounts for loss of manure N prior to soil application during transport, treatment, and storage, including both volatilization and leaching/runoff.

Estimated direct and indirect N_2O emissions by sub-source category are provided in Table 6-15 and Table 6-16.

Table 6-15: Direct N_2O Emissions from Agricultural Soils by Land-Use and N Input (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Cropland	**222.1**	**214.2**	**250.5**	**252.6**	**234.0**	**226.4**	**220.9**	**234.2**
Mineral Soils	**219.3**	**211.4**	**247.6**	**249.7**	**231.1**	**223.5**	**217.9**	**231.2**
Synthetic Fertilizer	83.6	85.1	91.9	94.2	90.2	84.6	88.5	86.9
Organic Amendment [a]	10.3	10.9	12.1	12.9	12.0	11.2	11.6	11.7
Residue N [b]	15.0	15.8	18.5	16.6	15.1	18.3	14.7	16.0
Other [c]	110.3	99.6	125.1	126.0	113.8	109.4	103.1	116.6
Organic Soils	**2.8**	**2.8**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**	**2.9**
Grassland	**88.0**	**77.8**	**73.9**	**74.8**	**80.1**	**71.0**	**71.3**	**76.4**
Synthetic Fertilizer	2.0	1.7	1.6	1.7	1.8	1.6	1.7	1.7
PRP Manure	16.4	15.8	16.8	15.3	20.6	15.5	17.2	14.3
Managed Manure [d]	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4
Sewage Sludge	0.2	0.4	0.5	0.5	0.5	0.5	0.5	0.5
Residue N [b]	34.4	29.9	28.1	29.9	28.0	27.9	26.4	29.8
Other [c]	34.5	29.6	26.5	27.0	28.8	25.2	25.0	29.7
Total	**310.1**	**292.0**	**324.4**	**327.4**	**314.1**	**297.4**	**292.1**	**310.5**

+ Less than 0.05 Tg CO_2 Eq.
[a] Organic amendment inputs include managed manure amendments and other commercial organic fertilizer (i.e., dried blood, dried manure, tankage, compost, and other).
[b] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.
[c] Other N inputs include mineralization from decomposition of soil organic matter as well as asymbiotic fixation of N from the atmosphere.
[d]Accounts for managed manure that is applied to grassland soils

Table 6-16: Indirect N_2O Emissions from all Land Use Types and Managed Manure Systems (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005
Cropland	**27.2**	**27.2**	**25.0**	**26.1**	**22.5**	**25.7**	**20.1**	**26.2**
Volatilization and Atm. Deposition	4.6	4.9	5.3	4.9	5.0	5.4	5.3	5.4
Surface Leaching & Run-Off	22.6	22.3	19.7	21.2	17.5	20.3	14.8	20.7
Grassland	**20.4**	**24.3**	**17.1**	**25.1**	**18.9**	**16.5**	**16.0**	**17.8**
Volatilization and Atm. Deposition	10.7	10.3	9.3	9.4	9.3	9.4	9.1	9.9
Surface Leaching & Run-Off	9.6	14.0	7.8	15.7	9.5	7.1	6.9	7.9
Managed manure systems	**7.5**	**8.0**	**8.4**	**8.5**	**8.7**	**8.5**	**8.5**	**8.5**
Volatilization and Atm. Deposition[a]	7.5	8.0	8.4	8.5	8.7	8.5	8.5	8.5
Forest Land	**+**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Volatilization and Atm. Deposition	+	+	+	+	+	+	+	+
Surface Leaching & Run-Off	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Settlements	**1.7**	**1.8**	**1.8**	**1.8**	**1.9**	**1.9**	**2.0**	**1.9**
Volatilization and Atm. Deposition	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Surface Leaching & Run-Off	1.2	1.2	1.3	1.2	1.3	1.3	1.3	1.3
Total	**56.8**	**61.4**	**52.4**	**61.6**	**52.0**	**52.8**	**46.6**	**54.6**

+ Less than 0.05 Tg CO_2 Eq.
[a] Accounts for loss of manure N prior to soil application during transport, treatment, and storage.

Figure 6-3 through Figure 6-6 show regional patterns in N_2O emissions for direct sources and regional patterns of N losses leading to indirect N_2O emissions, respectively, for major crops and grasslands across the United States. Direct N_2O emissions tend to be high in the Corn Belt (Illinois, Iowa, Southern Minnesota and Wisconsin, and Eastern Nebraska). A large portion of the land in many of these counties is covered with high input corn and N-fixing soybean cropping, resulting in high emissions on a per county basis. Emissions are also high in some counties in the Dakotas, Kansas, Eastern Colorado, Oklahoma, and Texas. High input irrigated cropping and moderate input dryland wheat cropping are major contributors to emissions in these counties. Emissions are high along the lower Mississippi Valley because this area is intensively cropped and fine-textured soils along the river facilitate denitrification and high N_2O emissions. Emissions are also high in some counties in California where intensive, irrigated cropping is a dominant land use. Emissions are low in the eastern United States because a small portion of land in most of these counties is cropped, and also low in many counties in the West where rainfall and access to irrigation water are limited. Counties with less than a minimum number of cropped acres were not simulated by DAYCENT (white areas). Emissions from these counties were calculated at the national scale using Tier 1 methodology.

Direct emissions (Tg CO_2 Eq./county/year) from grasslands are highest in the western United States (Figure 6-4) where counties tend to be large and a high proportion of the land in many of these counties is used for cattle grazing. Some counties in the Great Lake states, the Northeast, and Florida have moderate county level emissions even though emissions from these areas tend to be high on a per unit area basis, because the total amount of grazed land in these counties is much less than many counties in the West.

Indirect emissions for crops and grasslands (Figure 6-5 and Figure 6-6) show patterns similar to direct emissions, because the factors that control direct emissions (N inputs, weather, soil type) also influence indirect emissions. However, there are some exceptions, because the processes that contribute to indirect emissions (NO_3 leaching, N volatilization) do not respond in exactly the same manner to these controls as the processes that control direct emissions (nitrification and denitrification). For example, coarse-textured soils facilitate nitrification and moderate direct emissions in Florida grasslands, but indirect emissions are relatively high in Florida grasslands due to high rates of N volatilization and NO_3 leaching in coarse-textured soils. Indirect emissions from crops in some counties in the Carolinas are also relatively high compared to direct emissions because these soils tend to be coarse-textured.

Figure 6-3: Major Crops, Average Annual Direct N_2O Emissions, 1990-2005 (Tg CO_2 Eq./county/year)

Figure 6-4: Grasslands, Average Annual Direct N_2O Emissions, 1990-2005 (Tg CO_2 Eq./county/year)

Figure 6-5: Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990-2005 (Tg CO_2 Eq./county/year)

Figure 6-6: Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990-2005 (Tg CO_2 Eq./county/year)

Methodology

The *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) divide the Agricultural Soil Management source category into three components: (1) direct emissions from agricultural soils due to N additions to cropland and grassland mineral soils, planting of legumes on cropland and grassland soils, and drainage and cultivation of organic cropland soils; (2) direct emissions from soils due to the deposition of manure by livestock on PRP grasslands; and (3) indirect emissions from soils and water due to N additions and manure deposition to soils that leads to volatilization, leaching, or runoff of N and subsequent conversion to N_2O. Moreover, the *2006 IPCC Guidelines* (IPCC 2006) recommend reporting total emissions from managed lands, and, therefore, this chapter includes estimates for direct emissions due to decomposition of soil organic matter and litter, and asymbiotic fixation of N from the atmosphere.[11]

The methodology used to estimate emissions from agricultural soil management in the United States is based on a combination of IPCC Tier 1 and 3 approaches. A Tier 3, process-based model (DAYCENT) was used to estimate direct emissions from major crops on mineral (i.e., non-organic) soils; as well as most of the direct emissions from grasslands. The Tier 3 approach is more refined for estimating N_2O emissions in the United States, accounting for more of the environmental and management influences on soil N_2O emissions than the IPCC Tier 1 method (see Box 6-1 for further elaboration). The Tier 1 IPCC methodology was used to estimate direct emissions from non-major crops on mineral soils, the portion of the grassland direct emissions that were not estimated with the Tier 3 DAYCENT model, and direct emissions from drainage and cultivation of organic cropland soils. The Tier 1 approach was based on the *2006 IPCC Guidelines* (IPCC 2006), which was originally developed in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) and IPCC Good Practice Guidance Reports (IPCC 2000, 2003). A combination of DAYCENT and the IPCC Tier 1 method was used to estimate indirect emissions from soils.

The Agricultural Soil Management sector has adopted several recommendations from IPCC (2006) that are considered improvements over previous IPCC methods, including: (1) estimating the contribution of N from crop residues to indirect soil N_2O emissions, (2) adopting the revised emission factor for direct N_2O emissions, (3) removing double counting of emissions due to estimating N-fixing crops in both the symbiotic and crop residue N input categories, (4) using revised crop residue statistics to compute N inputs to soil based on harvest yield data, and (5) accounting for indirect as well as direct emissions from N made available via mineralization of soil organic matter and litter, in addition to asymbiotic fixation (i.e., computing total emissions from managed land). Annex 3.11 provides more detailed information on the methodologies and data used to calculate N_2O emissions from each component.

[BEGIN BOX]

Box 6-1. Tier 1 vs. Tier 3 Approach for Estimating N_2O Emissions

The Tier 1 approach (IPCC 2006) is based on multiplying activity data on different N sources (e.g., synthetic fertilizer, manure, N fixation, etc.) by the appropriate default IPCC emission factors to estimate N_2O emissions on a source-by-source basis. The Tier 3 approach developed for this Inventory employs a process-based model (i.e., DAYCENT) and is based on the interaction of N inputs and the environmental conditions at a specific location. Consequently, it is necessary not only to know the amount of N inputs but also the conditions under which the anthropogenic activity is increasing mineral N in a soil profile. The Tier 1 approach requires a minimal amount of activity data, readily available in most countries (e.g., total N applied to crops); calculations are simple; and the methodology is highly transparent. The Tier 3 approach is thought to produce more accurate estimates; it accounts for land-use and management impacts and their interaction with environmental factors (i.e., weather patterns and soil characteristics), which may enhance or dampen anthropogenic influences. However, the Tier 3 approach requires more refined activity data (e.g., crop-specific N amendment rates, daily weather, soil types, etc.) and considerable computational resources and programming expertise. The Tier 3 methodology is less transparent. Another important difference between the Tier 1 and Tier 3 approaches relates to assumptions regarding N cycling. Tier 1 assumes that N added to a system is subject to N_2O emissions only during that year; e.g., N added as fertilizer or through fixation contributes to N_2O emission for that year, but cannot be stored in soils and contribute to N_2O

[11] N inputs from asymbiotic N fixation are not directly addressed in 2006 IPCC Guidelines, but are a component of the total emissions from managed lands and are included in the Tier 3 approach developed for this Inventory.

emission in subsequent years. In contrast, the process-based model used in the Tier 3 approach includes such legacy effects when N is mineralized from soil organic matter and emitted as N_2O during subsequent years.

[END BOX]

Direct N_2O Emissions from Cropland Soils

Major Crop Types on Mineral Cropland Soils

The DAYCENT ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from mineral cropland soils that are managed for production of major crops, specifically corn, soybean, wheat, alfalfa hay, other hay, sorghum, and cotton, representing approximately 90 percent of total croplands in the United States. DAYCENT simulated crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions, and the simulations were driven by model input data generated from daily weather records (Thornton et al. 1997, 2000; Thornton and Running 1999), land management surveys (see citations below), and soil physical properties determined from national soil surveys (Soil Survey Staff 2005).

DAYCENT simulations were conducted for each major crop at the county scale in the United States. The county scale was selected, because soil and weather data were available for every county with more than 100 acres of agricultural land. However, land management data (e.g., timing of planting, harvesting, intensity of cultivation) were only available at the agricultural region level as defined by the Agricultural Sector Model (McCarl et al. 1993). There are 63 agricultural regions in the contiguous United States, and most states correspond to one region, except for those states with greater heterogeneity in agricultural practices, where there are further subdivisions. While several cropping systems were simulated for each county in an agricultural region with county-level weather and soils data, the model parameters that determined the influence of management activities on soil N_2O emissions (e.g., when crops were planted/harvested) did not differ among the counties in an agricultural region. Consequently, the results will best represent emissions at the regional and national levels due to the scale of management data.

Nitrous oxide emission estimates from DAYCENT include the influence of N additions, crop type, irrigation, and other factors in aggregate, and, therefore, it is not possible to partition N_2O emissions by anthropogenic activity directly from model outputs (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). Nitrous oxide emissions from managed agricultural lands are the result of interactions between the combined anthropogenic interventions that are implemented (e.g., N fertilization, manure application, tillage) and other driving variables, such as weather and soil characteristics. These factors influence key processes associated with N dynamics in the soil profile, including immobilization of N by soil microbial organisms, decomposition of organic matter, plant uptake, leaching, runoff, and volatilization, as well as the processes leading to N_2O production (nitrification and denitrification). According to IPCC/UNEP/OECD/IEA (1997), soil N_2O inventories are expected to report emissions from mineral soils associated with mineral N fertilization, organic amendments, crop residue N added to soils, and symbiotic N-fixation. In addition, IPCC (2006) recommends reporting total N_2O emissions from managed lands, which would also include “other N Inputs” from mineralization due to decomposition of soil organic matter and litter, as well as asymbiotic fixation of N from the atmosphere. To approximate emissions by activity, the amount of mineral N added to the soil for each of these practices was determined and then divided by the total amount of mineral N that was made available in the soil according to the DAYCENT model. The percentages were then multiplied by the total N_2O emissions in order to approximate the portion attributed to key practices. This approach is not precise because it assumes that all N made available in soil has an equal probability of being released as N_2O, regardless of its source, which is unlikely to be the case. Since it is not possible to track N flows from different sources using the DAYCENT model, this approach allows for further disaggregation by source of N, which is valuable for reporting purposes.

Consequently, DAYCENT was used to estimate direct N_2O emissions due to mineral N available from: (1) the application of synthetic fertilizers, (2) the application of livestock manure, (3) the retention of crop residues (i.e., leaving residues in the field after harvest), and (4) mineralization of soil organic matter and litter, in addition to asymbiotic fixation. This last source is generated internally by the DAYCENT model. For each of the first 3 practices, annual increases in soil mineral N due to anthropogenic activity were obtained or derived from the following sources:

- Crop-specific N-fertilization rates: Data sources for fertilization rates include Alexander and Smith (1990), Anonymous (1924), Battaglin and Goolsby (1994), Engle and Makela (1947), ERS (1994, 2003), Fraps and Asbury (1931), Ibach and Adams (1967), Ibach et al. (1964), NFA (1946), NRIAI (2003), Ross and Mehring (1938), Skinner (1931), Smalley et al. (1939), Taylor (1994), USDA (1966, 1957, 1954, 1946). Information on fertilizer use and rates by crop type for different regions of the United States were obtained primarily from the USDA Economic Research Service Cropping Practices Survey (ERS 1997) with additional data from other sources, including the National Agricultural Statistics Service (NASS 1992, 1999, 2004).

- Managed manure production and application to croplands and grasslands: Manure N amendments applied to croplands and grasslands (not including PRP manure) were determined using USDA Manure N Management Databases for 1997 (Kellogg et al. 2000; Edmonds et al. 2003). These values were scaled to estimate values for other years based on estimates of annual production of managed manure. The amount of managed manure for each livestock type was calculated by determining the population of animals that were on feedlots or otherwise housed in order to collect and manage the manure. Annual animal population data for all livestock types, except horses and goats, were obtained for all years from the U.S. Department of Agriculture-National Agricultural Statistics Service (USDA 1994a-b, 1995a-b, 1998a-b, 1999a-c, 2000a, 2004a-e, 2005a-d, 2006a). Horse population data were obtained from the FAOSTAT database (FAO 2006). Goat population data for 1992, 1997, and 2002 were obtained from the Census of Agriculture (USDA 2005g); these data were interpolated and extrapolated to derive estimates for the other years. Information regarding the poultry turnover (i.e., slaughter) rate was obtained from state Natural Resource Conservation Service personnel (Lange 2000). Additional population data for different farm size categories for dairy and swine were obtained from the 1992 and 1997 *Census of Agriculture* (USDA 2005g). These values may be slightly high because about 5 percent of poultry manure is used for feed (Carpenter 1992). However, poultry manure production is relatively small compared to other livestock categories, particularly cattle. Only a portion of the managed manure N is applied to crop and grassland soils according to Edmonds et al. (2003). The difference between manure N applied to soils and remaining N in the managed manure was assumed to be lost through volatilization and leaching/runoff of N species during treatment, storage, and transportation. Instead of assuming that 20 percent of organic N applied to soils is volatilized and 30 percent of applied N was lost through leaching/runoff, as approximated with IPCC (2006) methodology, volatilization and N leaching/runoff from manure that was amended to soils was calculated by the DAYCENT process-based model. Frequency and rates of manure application to cropland during the Inventory period were estimated from data compiled by the USDA Natural Resources Conservation Service for 1997 (Edmonds et al. 2003), with adjustments based on managed manure N excretion in other years of the Inventory.

- Nitrogen-fixing crops and forages, retention of crop residue, N mineralization from soil organic matter, and asymbiotic N fixation from the atmosphere: The IPCC approach considers this information as separate activity data. However, they are not considered separate activity data for the DAYCENT simulations because residue production, N fixation, mineralization of N from soil organic matter, and asymbiotic fixation are internally generated by the model. In other words, DAYCENT accounts for the influence of N fixation, mineralization of N from soil organic matter, and retention of crop residue on N_2O emissions, but these are not model inputs. The total input of N from these sources is determined during the model simulations.

- Historical and modern crop rotation and management information (e.g., timing and type of cultivation, timing of planting/harvest, etc.): These activity data were derived from Hurd (1930, 1929), Latta (1938), Iowa State College Staff Members (1946), Bogue (1963), Hurt (1994), USDA (2004f), USDA (2000b) as extracted by Eve (2001) and revised by Ogle (2002), CTIC (1998), Piper et al. (1924), Hardies and Hume (1927), Holmes (1902, 1929), Spillman (1902, 1905, 1907, 1908), Chilcott (1910), Smith (1911), Kezer (ca. 1917), Hargreaves (1993), ERS (2002), Warren (1911), Langston et al. (1922), Russell et al. (1922), Elliott and Tapp (1928), Elliott (1933), Ellsworth (1929), Garey (1929), Hodges et al. (1930), Bonnen and Elliott (1931), Brenner et al. (2002, 2001), and Smith et al. (2002).

DAYCENT-generated per-area estimates of N_2O emissions (g N_2O-N m^{-2}) from major crops were multiplied by the cropland area data to obtain county-scale emission estimates. Cropland area data were from NASS (USDA 2005g). The emission estimates by reported crop areas in the county were scaled to the regions, and the national estimate was calculated by summing results across all regions. DAYCENT is sensitive to actual interannual variability in weather patterns and other controlling variables, and so emissions associated with individual activities vary through time even if the management practices remain the same (e.g., if N fertilization remains the same for two years). In contrast, Tier 1 methods do not capture this variability and rather have a linear, monotonic response that depends solely on management practices. DAYCENT's ability to capture these interactions between management and environmental conditions enables it to produce more accurate estimates of N_2O emissions.

Non-Major Crop Types on Mineral Cropland Soils

The Tier 1 methodology (IPCC/UNEP/OECD/IEA 1997, IPCC 2006) was used to estimate direct N_2O emissions for mineral cropland soils that are managed for production of non-major crop types. Estimates of direct N_2O emissions from N applications to non-major crop types were based on mineral soil N that was made available from the following practices: (1) the application of synthetic commercial fertilizers, (2) application of non-manure other commercial organic fertilizers;[12] and (3) the retention of above- and below-ground crop residues. No manure amendments were considered here because most of this material was applied to crops simulated by DAYCENT. DAYCENT simulations included the 5 major cropping systems (corn, hay, sorghum, soybean, wheat), which are the land management systems receiving the vast majority (approximately 95 percent) of manure applications to cropped land in the United States (Kellogg et al. 2000, Edmonds et al. 2003). Non-manure organic amendments were not included in the DAYCENT simulations, because county-level data for this source were not available and this source is a very small portion of total organic amendments. Consequently, non-manure organic amendments were included in the Tier 1 analysis.

1. A process-of-elimination approach was used to estimate N fertilizer additions for these crops, because little information exists on fertilizer application rates for non-major crop types. N fertilizer additions to major crops, grassland, forest land, and settlements were summed, this sum was subtracted from total annual fertilizer sales, and the difference was assumed to be applied to non-major crop types. Non-major crop types include: (a) fruits, nuts, and vegetables, and (b) other annual crops not simulated by DAYCENT (barley, oats, tobacco, sugarcane, sugar beets, sunflowers, millet, peanuts, etc.).

2. Annual non-manure organic fertilizer additions were based on organic fertilizer consumption statistics, which were converted to units of N using average organic fertilizer N content statistics (TVA 1991, 1992a, 1993, 1994; AAPFCO 1995, 1996, 1997, 1998, 1999, 2000a, 2000b, 2002, 2003, 2004, 2005, 2006).

3. Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (1994a, 1998b, 2003, 2005i, 2006b), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

The total increase in soil mineral N from applied fertilizers and crop residues was multiplied by the IPCC (2006) default emission factor (Bouwman et al. 2002a, 2002b, Novoa and Tejeda 2006, Stehfest and Bouwman 2006) to derive an estimate of cropland direct N_2O emissions from non-major crop types.

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[12] Other commercial organic fertilizers include dried blood, dried manure, tankage, compost, other, but excludes manure and sewage sludge, which are used as commercial fertilizers.

Drainage and Cultivation of Organic Cropland Soils

Tier 1 methods were used to estimate direct N_2O emissions from the drainage and cultivation of organic cropland soils. Estimates of the total U.S. acreage of drained organic soils cultivated annually for temperate and sub-tropical climate regions were obtained for 1982, 1992, and 1997 from the Natural Resources Inventory (USDA 2000b, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1994, 1998). These areas were linearly interpolated and extrapolated to estimate areas for the missing years. To estimate annual emissions, the total temperate area was multiplied by the IPCC default emission factor for temperate regions, and the total sub-tropical area was multiplied by the average of the IPCC default emission factors for temperate and tropical regions (IPCC 2006).

Direct N_2O Emissions from Grassland Soils

As with N_2O from croplands, the Tier 3 process-based DAYCENT model and Tier 1 methods described in the IPCC (2006) guidelines were combined to estimate emissions from grasslands. Grasslands include pastures and rangelands used for grass forage production, where the primary use is livestock grazing. Rangelands are typically extensive areas of native grasslands that are not intensively managed, while pastures are often seeded grasslands, possibly following tree removal, that may or may not be improved with practices such as irrigation and interseeding legumes.

DAYCENT was used to simulate N_2O emissions from grasslands at the county scale resulting from manure deposited by livestock directly onto the pasture (i.e., PRP manure, which is simulated internally within the model), N fixation from legume seeding, managed manure amendments (i.e., manure other than PRP manure), and synthetic fertilizer application. The simulations used the same weather and soils data as discussed under the section for Major Crop Types on Mineral Cropland Soils. Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using managed manure N production data according to methods described in Annex 3.11. "other N inputs" were simulated within the DAYCENT framework, including N input from mineralization due to decomposition of soil organic matter and plant litter, as well as asymbiotic fixation of N from the atmosphere and atmospheric N deposition.

DAYCENT-generated per-area estimates of N_2O emissions (g N_2O-N m^{-2}) from pasture and rangelands were multiplied by the reported pasture and rangeland areas in the county. Grassland area data were obtained from the National Resources Inventory (NRI) (USDA 2000b). The 1997 NRI area data for pastures and rangeland were aggregated to the county level to estimate the grassland areas for 1995 to 2005, and the 1992 NRI pasture and rangeland data were aggregated to the county level to estimate areas from 1990 to 1994. The county estimates were scaled to the regions, and the national estimate was calculated by summing results across all regions.

Manure N deposition from grazing animals is modeled internally within DAYCENT. Comparisons with estimates of total manure deposited on PRP (see Annex 3.11) showed that DAYCENT accounted for approximately 70 percent of total PRP manure. It is reasonable that DAYCENT did not account for all PRP manure, because the NRI data do not include some grassland areas such as federal grasslands. N_2O emissions from the portion of PRP manure N not accounted for by DAYCENT were estimated using the Tier 1 method with IPCC default emission factors (de Klein 2004, IPCC 2006). Sewage sludge was assumed to be applied on grasslands (but not included in the DAYCENT simulations) because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application was estimated from data compiled by EPA (1993, 1997, 1999, 2003), Bastian (2002, 2003, 2005), and Metcalf and Eddy (1991). Sewage sludge data on soil amendments in agricultural lands were only available at the national scale, and it was not possible to associate application with specific soil conditions and weather at the county scale. Consequently, emissions from sewage sludge were also estimated using the Tier 1 method with IPCC default emission factors (Bouwman et al. 2002a, 2002b, Novoa and Tejeda 2006, Stehfest and Bouwman 2006, IPCC 2006). Emission estimates from DAYCENT and the IPCC method were summed to provide total national emissions for grasslands in the United States.

Annual direct emissions from major and non-major crops on mineral cropland soils, from drainage and cultivation of organic cropland soils, and from grassland soils were summed to obtain total direct N_2O emissions from agricultural soil management (see Table 6-13 and Table 6-14).

Indirect N_2O Emissions from Managed Soils of all Land-Use Types and Managed Manure Systems

This section describes methods for estimating indirect soil N_2O emissions from all land-use types (i.e., cropland, grassland, forest land, and settlements) and managed manure systems based on losses of N through volatilization, leaching, and runoff. The sources of indirect N from volatilization, leaching, and runoff are estimated in the same manner as direct N_2O emissions from soils (i.e., using DAYCENT and the Tier 1 method as described for direct emissions). The indirect emissions from these N sources are estimated using the Tier 1 method (IPCC 2006). Indirect N_2O emissions occur when mineral N made available through anthropogenic activity is transported from the soil either in gaseous or aqueous forms and later converted into N_2O. There are two pathways leading to indirect emissions. The first pathway results from volatilization of N as NO_x and NH_3 following application of synthetic fertilizer or organic amendments (e.g., manure, sewage sludge); deposition of PRP manure; or during storage, treatment, and transport of managed manure. N made available from mineralization of soil organic matter and asymbiotic fixation also contributes to volatilized N emissions. Through atmospheric deposition, volatilized N can be returned to soils, and a portion is emitted to the atmosphere as N_2O. The second pathway occurs via leaching and runoff of soil N (primarily in the form of nitrate [NO_3^-]) that was made available through anthropogenic activity on managed lands, mineralization of soil organic matter, asymbiotic fixation, and atmospheric deposition. The nitrate is subject to denitrification in water bodies, which leads to additional N_2O emissions. Regardless of the eventual location of the indirect N_2O emissions, the emissions are assigned to the original source of the N for reporting purposes, which here includes croplands, grasslands, forest lands, and settlements.

Indirect N_2O Emissions from Atmospheric Deposition of N Volatilized by Managed Soils and Managed Manure Systems

Similar to the direct emissions calculation, several approaches were combined to estimate the amount of applied N that was exported from application sites through volatilization. DAYCENT was used to simulate the amount of N transported from land areas whose direct emissions were simulated with DAYCENT (i.e., major croplands and most grasslands), while the IPCC method was used for land areas that were not simulated with DAYCENT (i.e., non-major croplands and a small portion of grasslands) (IPCC 2006). Manure N from managed systems assumed to be volatilized during storage, treatment, and transport was also estimated and included as a source of N for indirect emissions.

The N volatilized from managed agricultural, forest land, and settlement soils, in addition to volatilization during storage, treatment, and transport of managed manure was summed to obtain total volatilization. N lost from storage, treatment, and transport of managed manure is counted as volatilized even though some of this N is likely to be leached/runoff. This is a conservative approach because the IPCC emission factor for volatilization is slightly higher than for leaching/runoff (IPCC 2006). The IPCC default emission factor (Brumme et al. 1999, Butterbach-Bahl et al. 1997, Corre et al. 1999, Denier van der Gon and Bleeker 2005, IPCC/UNEP/OECD/IEA 1997, IPCC 2006) was applied to the total amount of N volatilized to estimate indirect N_2O emissions from volatilization due to the use and management of U.S. croplands, grasslands, forest lands, settlements and managed manure (Table 6-16).

Indirect N_2O from Leaching/Runoff

Similar to the indirect emissions calculation from volatilized N, several approaches were combined to estimate the amount of applied N that was transported from application sites through leaching and surface runoff into waterbodies. DAYCENT was used to simulate the amount of N transported from major cropland types and most grasslands, while N transport from non-major croplands and grasslands not addressed in the DAYCENT model simulations (i.e., from land areas that were not simulated with DAYCENT), settlements, and forestland were obtained by applying the IPCC default fractions for leaching and runoff (IPCC/UNEP/OECD/IEA 1997, IPCC 2006) to total N made available from fertilizer applied, manure applied or deposited, above- and below-ground crop residue retention, soil organic matter decomposition, and asymbiotic fixation.

The N leached/runoff from managed soils, forests, and settlements was summed to obtain total N leaching or surface runoff. The IPCC default emission factor was applied to the total amount of N leached/runoff to estimate total indirect N_2O emissions due to the use and management of croplands, grasslands, forest lands, and settlements (Table

6-16) (IPCC 2006).

Uncertainty

Uncertainty was estimated differently for each of the following three components of N_2O emissions from agricultural soil management: (1) direct emissions calculated by DAYCENT, (2) direct emissions not calculated by DAYCENT, and (3) indirect emissions.

For direct emissions calculated using DAYCENT, uncertainty in the results was attributed to model inputs and the structure of the model (i.e., underlying model equations and parameterization). A Monte Carlo analysis was implemented to address these uncertainties and propagate errors through the modeling process (Del Grosso et al., in prep). A Monte Carlo analysis was conducted using probability distribution functions (PDFs) for weather, soil characteristics, and N inputs to simulate direct N_2O emissions for each crop- or grassland type in a county. A joint PDF was used to address the structural uncertainty for direct N_2O emissions from crops, which was derived using an empirically-based method (Ogle et al. 2007).

County-scale PDFs for weather were based on the variation in temperature and precipitation as represented in DAYMET weather data grid cells (1x1 km) occurring in croplands and grasslands in a county. The National Land Cover Dataset (Vogelman et al. 2001) provided the data on distribution of croplands and grasslands. Similarly, county-scale PDFs for soil characteristics were based on STATSGO Soil Map Units (Soil Survey Staff 2005), that occurred in croplands and grasslands. PDFs for fertilizer were derived from survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure applications for specific crops was incorporated into the analysis based on total manure available for application in each county, a weighted average application rate, and the crop-specific land area amended with manure for 1997 (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments; see Edmonds et al. 2003). Together with the total area for each crop within a county, the result yielded a probability that a given crop in a specific county would either receive manure or not in the Monte Carlo analysis. A ratio of manure N production in each year of the Inventory relative to 1997 was used to adjust the amount of area amended with manure, under the assumption that greater or less manure N production would lead to a proportional change in amended area (see the section on Major Crop Types on Mineral Soils for data sources on manure N production). If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., producers often reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates (ERS 1997).

An empirically-based uncertainty estimator was developed using a method described by Ogle et al. (2007) to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed-effect modeling analysis comparing N_2O emission estimates from eight agricultural experiments with 50 treatments. Although the dataset was relatively small, modeled emissions were significantly related to measurements with a p-value of less than 0.01. Random effects were included to capture the dependence in time series and data collected from the same experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. The structural uncertainty estimator accounted for bias and prediction error in the DAYCENT model results, as well as random error associated with fine-scale emission predictions in counties over a time series from 1990 to 2005. Note that the current application only addresses structural uncertainty in cropland estimates; further development will be needed to address these uncertainties in model estimates for grasslands, which is a planned improvement as more soil N_2O measurement data become available for grassland sites. In general, DAYCENT tended to underestimate emissions if the rates were above 6 g N_2O m^{-2} (Del Grosso et al., in prep).

A simple error propagation method (IPCC 2006) was used to estimate uncertainties for direct emissions from mineral N inputs estimated with Tier 1 methods, including management on croplands that were used to produce minor crops and N inputs on grasslands that were not addressed in the DAYCENT simulations. Similarly, indirect emissions from agricultural soil management, which were calculated according to the IPCC methodology, were estimated using the simple error propagation method (IPCC 2006).

Uncertainties from Tier 3 and Tier 1 approaches were combined using simple error propagation (IPCC 2006). The results of the uncertainty analysis are summarized in Table 6-17. Agricultural direct soil N_2O emissions in 2005 were estimated to be between 247.5 and 380.0 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 20 percent below and 22 percent above the actual 2005 emission estimate of 310.5 Tg CO_2 Eq. The indirect soil N_2O emissions in 2005 were estimated to range from 31.9 to 128.4 Tg CO_2 Eq. at a 95 percent confidence level, indicating an uncertainty of 42 percent below and 135 percent above the actual 2005 emission estimate of 54.6 Tg CO_2 Eq.

Table 6-17: Quantitative Uncertainty Estimates of N_2O Emissions from Agricultural Soil Management in 2005 (Tg CO_2 Eq. and Percent)

Source	Gas	2005 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Direct Soil N_2O Emissions	N_2O	310.5	247.5	380.0	-20%	22%
Indirect Soil N_2O Emissions	N_2O	54.6	31.9	128.4	-42%	135%

Note: Due to lack of data, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; every attempt will be made to include these sources of uncertainty in future Inventories.

QA/QC and Verification

For quality control, DAYCENT results for N_2O emissions and NO_3 leaching were compared with field data representing various cropped/grazed systems, soils types, and climate patterns (Del Grosso et al. 2005). N_2O measurement data were available for seven sites in the United States and one in Canada, representing 25 different combinations of fertilizer treatments and cultivation practices. NO_3 leaching data were available for three sites in the United States representing nine different combinations of fertilizer amendments. Linear regressions of simulated vs. observed emission and leaching data yielded correlation coefficients of 0.74 and 0.96 for annual N_2O emissions and NO_3 leaching, respectively.

Spreadsheets containing input data and PDFs required for DAYCENT simulations of major croplands and grasslands and unit conversion factors were checked, as well as the program scripts that were used to run the Monte Carlo Analysis. There is a pending problem with timing of management activities (e.g., planting dates, harvest) as scheduled in the DAYCENT simulations for sorghum production in some counties, and this issue has been prioritized for correction. Spreadsheets containing input data and emission factors required for the Tier 1 approach used for non-major crops and grasslands not simulated by DAYCENT were checked and no errors were found. Total emissions and emissions from the different categories were compared with inventories from previous years and differences were reasonable given the methodological differences (see Recalculations section for further discussion).

Recalculations Discussion

Major revisions in the Agricultural Soil Management sector this year included (1) modifying N inputs to be consistent with the agricultural soil C sector, (2) modeling within-county variation in soil characteristics and weather, (3) developing a Monte Carlo Analysis to address uncertainties in the DAYCENT results, (4) implementing a separate uncertainty analysis for direct emissions calculated with the IPCC default methodology, and (5) incorporating revised methods and emission factors from IPCC (2006).

In terms of N inputs, several changes were needed in order to achieve consistency between the agricultural soil N_2O and soil C inventories. First, the method for simulating mineral N fertilization was changed, so that application rates for major crops were assumed to be stable over the Inventory time period. Changes in the amount of fertilizer applied to soils were assumed to be a result of changing land area for application rather than the rate of application. Second, manure amendment data were altered, so that the area of application varied from year to year based on a county-scale ratio of manure production in an Inventory year relative to 1997. Therefore, the amount of area amended with manure varies through time as a function of the amount of manure. Third, N_2O emissions from soil application of sewage sludge were estimated using the Tier 1 methodology (IPCC 2006) instead of the DAYCENT model. DAYCENT simulates N_2O emissions at the county scale, but sewage sludge application data were only available at the national scale. This created a mismatch in the scale of the DAYCENT model analysis compared to input data availability. The Tier 1 method was assumed to better represent these emissions, since it was not possible with the current dataset to associate sewage sludge application with specific soil and weather conditions at the county scale. Fourth, non-manure commercial organic amendments to soils were assumed to be applied on fields used to produce minor crops, and N_2O emissions were estimated with the IPCC default methodology. Commercial organic fertilizers are more expensive than manure and mineral fertilizers, and, therefore, assumed to be used on cash crops (e.g., vegetables). Cash crops are considered non-major crops for purposes of the Inventory calculations, and, thus, estimated using the Tier 1 methods. Fifth, N inputs from forage legumes not accounted for by the DAYCENT simulations are no longer included in the emissions calculations. In the previous inventory, the difference between the total N inputs from forage legumes, estimated using an alternative approach, and the DAYCENT estimate was included in the N_2O emissions estimate. However, it was determined that DAYCENT is likely providing a reasonable estimate of total N inputs from forage legumes so the additional production from the alternative approach is no longer included.

In last year's Inventory, weather and soils data were based on the conditions at the centroid location of a county. However, conditions do vary across a county, so the analysis was modified to include sub-county scale heterogeneity in these data. The National Land Cover Dataset (Vogelman et al. 2001) was used to determine the overlap between cropland and DAYMET weather records, which are produced on a 1×1 km grid, as well as the soil map units from the STATSGO database that overlap with cropland. The same procedure was also used to determine heterogeneity in weather and soil characteristics for grasslands. PDFs were formed for each of these data inputs and used in a Monte Carlo uncertainty analysis.

The methods for Agricultural Soil Management have been revised in IPCC (2006), and key changes have been incorporated into this year's Inventory. First, the default emission factor for direct soil N_2O emissions was lowered from 1.25 to 1.0 percent of N inputs. Second, previously a portion of the N inputs were removed from the calculation of direct N_2O emissions because it was assumed to be lost through volatilization before direct emissions occurred. However, the direct emission factor was developed based on total N inputs, and therefore the new method has been revised to estimate direct N_2O emissions based on total N input. Third, unlike IPCC/UNEP/OECD/IEA (1997) that counted N fixed by legumes and transported to aboveground biomass as N inputs, as well as N in crop residues, the IPCC (2006) does not double-count symbiotic N fixation separately from the crop residue N inputs. However, the new method does incorporate crop N inputs from not only the aboveground residues, as in IPCC/UNEP/OECD/IEA (1997), but also the root N input to the soil as well. Fourth, regarding indirect emissions, only N inputs from synthetic and organic fertilizer additions were assumed to contribute to NO_3 runoff and leaching in IPCC/UNEP/OECD/IEA (1997). IPCC (2006) assumes that N from crop residues, which includes unharvested N that was symbiotically fixed, is also available for runoff and leaching. Sixth, the amount of N leached out of the soil profile or run off the soil surface that is assumed to be denitrified to N_2O in aquatic systems was lowered from 2.5 to 0.75 percent. Lastly, IPCC (2006) recommends reporting total emissions from managed lands because of the subjectivity with attempting to separate anthropogenic influences from "natural" emissions in a managed environment (i.e., all processes leading to N mineralization in a managed environment and resulting emissions are influenced by anthropogenic activity). Thus, N_2O emissions were not reduced by attempting to estimate a natural background emission based on simulating native vegetation, which had been done in the previous Inventory.

There are two main consequences of adopting new methods from IPCC (2006). First, total emissions are higher, in large part because the non-anthropogenic portion was not subtracted from total emissions. Second, indirect emissions are lower because the amount of nitrate N leached and runoff that is assumed to be converted to N_2O in waterways is substantially lower (0.75 versus 2.5 percent of nitrate N in IPCC/UNEP/OECD/IEA [1997]).

The total change following recalculations ranged from a 15 to 42 percent increase in emissions with an average increase of 32.5 per cent. As noted above, one reason for the increase is that under the new methods from IPCC

(2006) non-anthropogenic emissions were not subtracted from total emissions. The second main reason is that application of the structural uncertainty estimator described above tended to increase direct N_2O estimates, because DAYCENT under-estimated emissions when the annual rate exceeded 6 g N_2O m^{-2}.

Planned Improvements

Two major improvements are planned for the Agricultural Soil Management sector. The first improvement will be to incorporate more land survey data from the National Resources Inventory (NRI) (USDA 2000b) into the DAYCENT simulation analysis, beyond the area estimates for rangeland and pasture that are currently used to estimate emissions from grasslands. NRI has a record of land-use activities since 1982 for all U.S. agricultural land, which is estimated at about 386 Mha. NASS is used as the basis for land-use records in the current Inventory, and there are three major disadvantages to this land survey. First, most crops are grown in rotation with other crops (e.g., corn-soybean), but NASS data provide no information regarding rotation histories. In contrast, NRI is designed to track rotation histories, and this is important because emissions from any particular year can be influenced by the crop that was grown the previous year. Second, NASS does not conduct a complete survey of cropland area each year, leading to gaps in the land base. NRI does provide a complete history of cropland areas for 4 out of every 5 years, and is currently moving to an annualized inventory that will include a full record for each year. Third, the current Inventory based on NASS does not quantify the influence of land-use change on emissions, which can be addressed using the NRI survey records. NRI also provides additional information on pasture land management that can be incorporated into the analysis (particularly the use of irrigation). Using NRI data will also make the Agricultural Soil Management sector methods more consistent with the methods used to estimate C stock changes for agricultural soils. However, the structure of model input files that contain land management data will need to be extensively revised to facilitate use of NRI data.

The second planned improvement is to further refine the uncertainty analysis. New studies are being completed and published evaluating agricultural management impacts on soil N_2O emissions, and these studies can be incorporated into the empirical analysis, leading to a more robust assessment of structural uncertainty in DAYCENT. Moreover, structural uncertainty is only evaluated for emission estimates in croplands, but it is anticipated that the evaluation could be expanded in the near future to include grasslands. In addition, the Monte Carlo analysis will be expanded to address uncertainties in activity data related to crop- and grassland areas, as well as irrigation and tillage histories. Currently, the land-area statistics are treated as certain because the NASS data do not include a measure of uncertainty. Incorporating land survey data from the NRI will facilitate the assessment of uncertainties in agricultural activity data. Finally, uncertainties in managed manure N production, PRP manure N production, other organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain. Uncertainties in these quantities will be derived and included in future years.

Additional improvements are more minor but will lead to more accurate estimates, including updating DAYMET weather for more recent years and revising manure N application data to not include poultry manure that is used for cattle feed. Currently, it is estimated that approximately 5 percent of poultry manure is used for feed in the United States and, therefore, not applied to soils. Future inventories will also create a time series of poultry manure going to feed, since initial research indicates that the percentage may have changed over time. In addition, some simulations for sorghum did not run to completion. Input files for counties where this occurred will be examined and the errors corrected. Lastly, instead of assuming that a constant 10 percent of total fertilizer used annually in the US is applied to settlements, an attempt will be made in the future to recognize that this value varies through the time series because of increasing urbanization, particularly in metropolitan areas. This improvement will be accomplished by exploring the possibility of developing a database that has county-level nitrogen fertilizer data partitioned by farm and non-farm use.

6.5. Field Burning of Agricultural Residues (IPCC Source Category 4F)

Farming activities produce large quantities of agricultural crop residues, and farmers use or dispose of these residues in a variety of ways. For example, agricultural residues can be left on or plowed into the field, composted and then applied to soils, landfilled, or burned in the field. Alternatively, they can be collected and used as fuel, animal bedding material, supplemental animal feed, or construction material. Field burning of crop residues is not considered a net source of CO_2, because the carbon released to the atmosphere as CO_2 during burning is assumed to be reabsorbed during the next growing season. Crop residue burning is, however, a net source of CH_4, N_2O, CO, and NO_x, which are released during combustion.

Field burning is not a common method of agricultural residue disposal in the United States. The primary crop types whose residues are typically burned in the United States are wheat, rice, sugarcane, corn, barley, soybeans, and peanuts. Less than 5 percent of the residue for each of these crops is burned each year, except for rice.[13] Annual emissions from this source over the period 1990 to 2005 have remained relatively constant, averaging approximately 0.9 Tg CO_2 Eq. (41 Gg) of CH_4, 0.5 Tg CO_2 Eq. (2 Gg) of N_2O (see Table 6-18 and Table 6-19).

Table 6-18: CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq.)

Gas/Crop Type	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**0.7**	**0.7**	**0.8**	**0.8**	**0.7**	**0.8**	**0.9**	**0.9**
Wheat	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rice	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.3	0.3	0.4	0.3	0.3	0.4	0.4	0.4
Barley	+	+	+	+	+	+	+	+
Soybeans	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Peanuts	+	+	+	+	+	+	+	+
N_2O	**0.4**	**0.4**	**0.5**	**0.5**	**0.4**	**0.4**	**0.5**	**0.5**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Barley	+	+	+	+	+	+	+	+
Soybeans	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.3
Peanuts	+	+	+	+	+	+	+	+
Total	**1.1**	**1.0**	**1.3**	**1.2**	**1.1**	**1.2**	**1.4**	**1.4**

+ Less than 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.

Table 6-19: CH_4, N_2O, CO, and NO_x Emissions from Field Burning of Agricultural Residues (Gg)

Gas/Crop Type	1990	1995	2000	2001	2002	2003	2004	2005
CH_4	**33**	**32**	**38**	**37**	**34**	**38**	**42**	**41**
Wheat	7	5	5	5	4	6	5	5
Rice	4	4	4	4	3	5	4	4
Sugarcane	1	1	1	1	1	1	1	1
Corn	13	13	17	16	15	17	20	19
Barley	1	1	1	+	+	+	+	+
Soybeans	7	8	10	11	10	9	11	11
Peanuts	+	0	+	+	+	+	+	+
N_2O	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**
Wheat	+	+	+	+	+	+	+	+
Rice	+	+	+	+	+	+	+	+
Sugarcane	+	+	+	+	+	+	+	+
Corn	+	+	+	+	+	+	+	+

[13] The fraction of rice straw burned each year is significantly higher than that for other crops (see "Methodology" discussion below).

Barley	+	+	+	+	+	+	+	+
Soybeans	1	1	1	1	1	1	1	1
Peanuts	+	+	+	+	+	+	+	+
CO	**691**	**663**	**792**	**774**	**709**	**800**	**879**	**858**
Wheat	137	109	112	98	80	117	108	105
Rice	87	88	78	81	64	100	78	91
Sugarcane	18	20	24	23	23	22	19	18
Corn	282	263	353	338	319	359	420	395
Barley	16	13	12	9	8	10	10	8
Soybeans	148	167	212	222	212	189	240	237
Peanuts	2	2	2	3	2	3	3	3
NO_x	**28**	**29**	**35**	**35**	**33**	**34**	**39**	**39**
Wheat	4	3	3	3	2	3	3	3
Rice	3	3	3	3	2	3	3	3
Sugarcane	+	+	+	+	+	+	+	+
Corn	7	6	8	8	8	9	10	9
Barley	1	+	+	+	+	+	+	+
Soybeans	14	16	20	21	20	18	23	22
Peanuts	+	+	+	+	+	+	+	+

\+ Less than 0.5 Gg
Note: Totals may not sum due to independent rounding.

Methodology

The methodology for estimating greenhouse gas emissions from field burning of agricultural residues is consistent with IPCC/UNEP/OECD/IEA (1997). In order to estimate the amounts of C and N released during burning, the following equations were used:[14]

[C or N] Released = (Annual Crop Production) × (Residue/Crop Product Ratio) × (Fraction of Residues Burned in situ) × (Dry Matter Content of the Residue) × (Burning Efficiency) × ([C or N] Content of the Residue) × (Combustion Efficiency)[15]

Emissions were calculated by multiplying the amount of C or N released by the appropriate IPCC default emission ratio (i.e., CH_4-C/C and, N_2O-N/N).

The types of crop residues burned in the United States were determined from various state-level greenhouse gas emission inventories (ILENR 1993, Oregon Department of Energy 1995, Wisconsin Department of Natural Resources 1993) and publications on agricultural burning in the United States (Jenkins et al. 1992, Turn et al. 1997, EPA 1992).

Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's *Field Crops, Final Estimates 1987-1992, 1992-1997, 1997-2002* (USDA 1994, 1998, 2003), and *Crop Production Summary* (USDA 2005, 2006). Rice production data for Florida and Oklahoma, which are not collected by USDA, were

[14] As is explained later in this section, the fraction of rice residues burned varies among states, so these equations were applied at the state level for rice. These equations were applied at the national level for all other crop types.

[15] Burning Efficiency is defined as the fraction of dry biomass exposed to burning that actually burns. Combustion Efficiency is defined as the fraction of carbon in the fire that is oxidized completely to CO_2. In the methodology recommended by the IPCC, the "burning efficiency" is assumed to be contained in the "fraction of residues burned" factor. However, the number used here to estimate the "fraction of residues burned" does not account for the fraction of exposed residue that does not burn. Therefore, a "burning efficiency factor" was added to the calculations.

estimated separately. Average primary and ratoon crop yields for Florida (Schueneman and Deren 2002) were applied to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005), and crop yields for Arkansas (USDA 1994, 1998, 2003, 2005, 2006) were applied to Oklahoma acreages[16] (Lee 2003, 2004, 2005, 2006). The production data for the crop types whose residues are burned are presented in Table 6-20.

The percentage of crop residue burned was assumed to be 3 percent for all crops in all years, except rice, based on state inventory data (ILENR 1993, Oregon Department of Energy 1995, Noller 1996, Wisconsin Department of Natural Resources 1993, and Cibrowski 1996). Estimates of the percentage of rice residue burned were derived from state-level estimates of the percentage of rice area burned each year, which were multiplied by state-level, annual rice production statistics. The annual percentages of rice area burned in each state were obtained from the agricultural extension agents in each state and reports of the California Air Resources Board (Anonymous 2006; Bollich 2000; California Air Resources Board 1999, 2001; Cantens 2005; Deren 2002; Fife 1999; Klosterboer 1999a, 1999b, 2000, 2001, 2002, 2003; Lancero 2006; Lee 2005, 2006; Lindberg 2002, 2003, 2004, 2005; Linscombe 1999a, 1999b, 2001, 2002, 2003, 2004, 2005, 2006; Najita 2000, 2001; Sacramento Valley Basinwide Air Pollution Control Council 2005; Schueneman 1999a, 1999b, 2001; Stansel 2004, 2005; Street 2001, 2002, 2003; Walker 2004, 2005, 2006; Wilson 2003, 2004, 2005, 2006) (see Table 6-21 and Table 6-22). The estimates provided for Florida and Missouri remained constant over the entire 1990 through 2005 period, while the estimates for all other states varied over the time series. For California, the annual percentages of rice area burned in the Sacramento Valley are assumed to be representative of burning in the entire state, because the Sacramento Valley accounts for over 95 percent of the rice acreage in California (Fife 1999). These values generally declined between 1990 and 2005 because of a legislated reduction in rice straw burning (Lindberg 2002), although there was a slight increase from 2004 to 2005 (see Table 6-21 and Table 6-22).

All residue/crop product mass ratios except sugarcane were obtained from Strehler and Stützle (1987). The datum for sugarcane is from University of California (1977). Residue dry matter contents for all crops except soybeans and peanuts were obtained from Turn et al. (1997). Soybean dry matter content was obtained from Strehler and Stützle (1987). Peanut dry matter content was obtained through personal communications with Jen Ketzis (1999), who accessed Cornell University's Department of Animal Science's computer model, Cornell Net Carbohydrate and Protein System. The residue carbon contents and nitrogen contents for all crops except soybeans and peanuts are from Turn et al. (1997). The residue C content for soybeans and peanuts is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The nitrogen content of peanuts is from Ketzis (1999). These data are listed in Table 6-23. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent, for all crop types (EPA 1994). Emission ratios for all gases (see Table 6-24) were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Table 6-20: Agricultural Crop Production (Gg of Product)

Crop	1990	1995	2000	2001	2002	2003	2004	2005
Wheat	74,292	59,404	60,641	53,001	43,705	63,814	58,738	57,280
Rice	7,114	7,947	8,705	9,794	9,601	9,084	10,565	10,152
Sugarcane	25,525	27,922	32,762	31,377	32,253	30,715	26,320	25,308
Corn	201,534	187,970	251,854	241,377	227,767	256,278	299,914	282,260
Barley	9,192	7,824	6,919	5,407	4,940	6,059	6,091	4,613
Soybeans	52,416	59,174	75,055	78,671	75,010	66,778	85,013	83,999
Peanuts	1,635	1,570	1,481	1,940	1,506	1,880	1,945	2,187

*Corn for grain (i.e., excludes corn for silage).

Table 6-21: Percent of Rice Area Burned by State

State	1990-1998	1999	2000	2001	2002	2003	2004	2005

[16] Rice production yield data are not available for Oklahoma, so the Arkansas values are used as a proxy.

Arkansas	13%	13%	13%	13%	16%	22%	17%	22%
California	Variable[a]	27%	27%	23%	13%	14%	11%	12%
Florida[b]	0%	0%	0%	0%	0%	0%	0%	0%
Louisiana	6%	0%	5%	4%	3%	3%	3%	3%
Mississippi	10%	40%	40%	40%	8%	65%	23%	23%
Missouri	18%	18%	18%	18%	18%	18%	18%	18%
Oklahoma	90%	90%	90%	90%	90%	100%	88%	94%
Texas	1%	2%	0%	0%	0%	0%	0%	0%

[a] Values provided in Table 6-22.
[b] Although rice is cultivated in Florida, crop residue burning is illegal. Therefore, emissions remain zero throughout the time series.

Table 6-22: Percent of Rice Area Burned in California, 1990-1998

Year	Percentage
1990	75%
1991	75%
1992	66%
1993	60%
1994	69%
1995	59%
1996	63%
1997	34%
1998	35%

Table 6-23: Key Assumptions for Estimating Emissions from Field Burning of Agricultural Residues

Crop	Residue/Crop Ratio	Fraction of Residue Burned	Dry Matter Fraction	C Fraction	N Fraction	Burning Efficiency	Combustion Efficiency
Wheat	1.3	0.03	0.93	0.4428	0.0062	0.93	0.88
Rice	1.4	Variable	0.91	0.3806	0.0072	0.93	0.88
Sugarcane	0.8	0.03	0.62	0.4235	0.0040	0.93	0.88
Corn	1.0	0.03	0.91	0.4478	0.0058	0.93	0.88
Barley	1.2	0.03	0.93	0.4485	0.0077	0.93	0.88
Soybeans	2.1	0.03	0.87	0.4500	0.0230	0.93	0.88
Peanuts	1.0	0.03	0.86	0.4500	0.0106	0.93	0.88

Table 6-24: Greenhouse Gas Emission Ratios

Gas	Emission Ratio
CH_4[a]	0.005
CO[a]	0.060
N_2O[b]	0.007
NO_x[b]	0.121

[a] Mass of C compound released (units of C) relative to mass of total C released from burning (units of C).
[b] Mass of N compound released (units of N) relative to mass of total N released from burning (units of N).

Uncertainty

A significant source of uncertainty in the calculation of non-CO_2 emissions from field burning of agricultural residues is in the estimates of the fraction of residue of each crop type burned each year. Data on the fraction burned, as well as the gross amount of residue burned each year, are not collected at either the national or state level. In addition, burning practices are highly variable among crops, as well as among states. The fractions of residue burned used in these calculations were based upon information collected by state agencies and in published literature. Based on expert judgment, uncertainty in the fraction of crop residue burned ranged from zero to 100 percent, depending on the state and crop type.

The results of the Tier 2 Monte Carlo uncertainty analysis are summarized in Table 6-25. CH_4 emissions from field burning of agricultural residues in 2005 were estimated to be between 0.75 and 0.97 Tg CO_2 Eq. at a 95 percent confidence level. This indicates a range of 13 percent below and 13 percent above the 2005 emission estimate of 0.9 Tg CO_2 Eq. Also at the 95 percent confidence level, N_2O emissions were estimated to be between 0.45 and 0.57 Tg CO_2 Eq. (or approximately 11 percent below and 12 percent above the 2005 emission estimate of 0.5 Tg CO_2 Eq.).

Table 6-25: Tier 2 Uncertainty Estimates for CH_4 and N_2O Emissions from Field Burning of Agricultural Residues (Tg CO_2 Eq. and Percent)

Source	**Gas**	**2005 Emission Estimate (Tg CO_2 Eq.)**	**Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)**		**(%)**	
			Lower Bound	**Upper Bound**	**Lower Bound**	**Upper Bound**
Field Burning of Agricultural Residues	CH_4	0.9	0.75	0.97	-13%	13%
Field Burning of Agricultural Residues	N_2O	0.5	0.45	0.57	-11%	12%

[a]Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

QA/QC and Verification

A source-specific QA/QC plan for field burning of agricultural residues was implemented. This effort included a Tier 1 analysis, as well as portions of a Tier 2 analysis. The Tier 2 procedures focused on comparing trends across years, states, and crops to attempt to identify any outliers or inconsistencies. No problems were found.

Recalculations Discussion

The crop production data for 2004 were updated using data from USDA (2006). Data on the percentage of rice residue burned in Missouri were revised for all years to 17.5 percent based on new information (Anonymous 2006). Similarly, the percentage of rice residue burned in Mississippi was revised to 22.5 percent for 2004 based on new information provided by Walker (2006). New data for acres of rice harvested in Arkansas in 2005 changed the average rice yield for Arkansas for all years. Subsequently, this change resulted in a change in the rice production data for Oklahoma for all years, since Arkansas data are used as a proxy to calculate rice production in Oklahoma.

These modifications resulted in a change in emissions estimates for CH_4 and N_2O for all years. From 1990 to 2004, emission estimates for CH_4 increased by amounts ranging between 0.18 and 0.51 percent. From 1990 to 2003, N_2O emission estimates increased by amounts ranging between 0.15 and 0.39 percent. In 2004, N_2O emission estimates decreased by 0.05 percent.

Planned Improvements

Preliminary research on agricultural burning in the United States indicates that residues from several additional crop types (e.g., grass for seed, blueberries, and fruit and nut trees) are burned. Whether sufficient information exists for inclusion of these additional crop types in future inventories is being investigated. The extent of recent state crop-burning regulations is also being investigated.

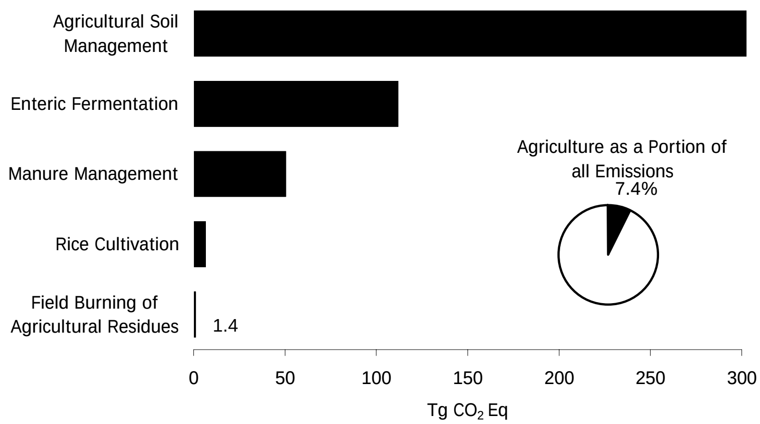
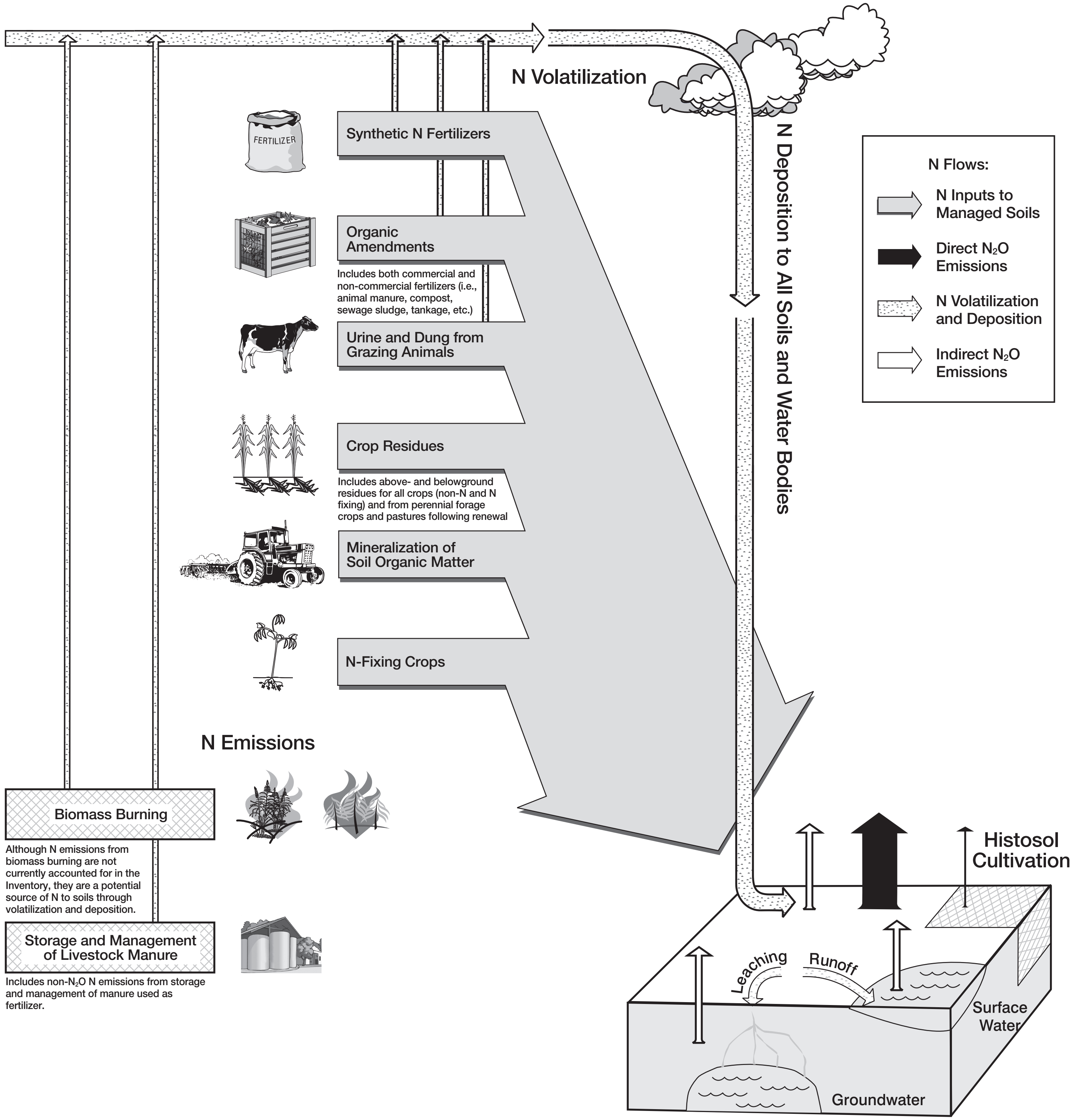


Figure 6-1: 2005 Agriculture Chapter GHG Sources



This graphic illustrates the sources and pathways of nitrogen that result in direct and indirect N_2O emissions from soils in the United States. Sources of nitrogen applied to, or deposited on, soils are represented with arrows on the left-hand side of the graphic. Emission pathways are also shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Figure 6-3

Major Crops, Average Annual Direct N_2O Emissions, 1990-2005 (Tg CO_2 Eq.)

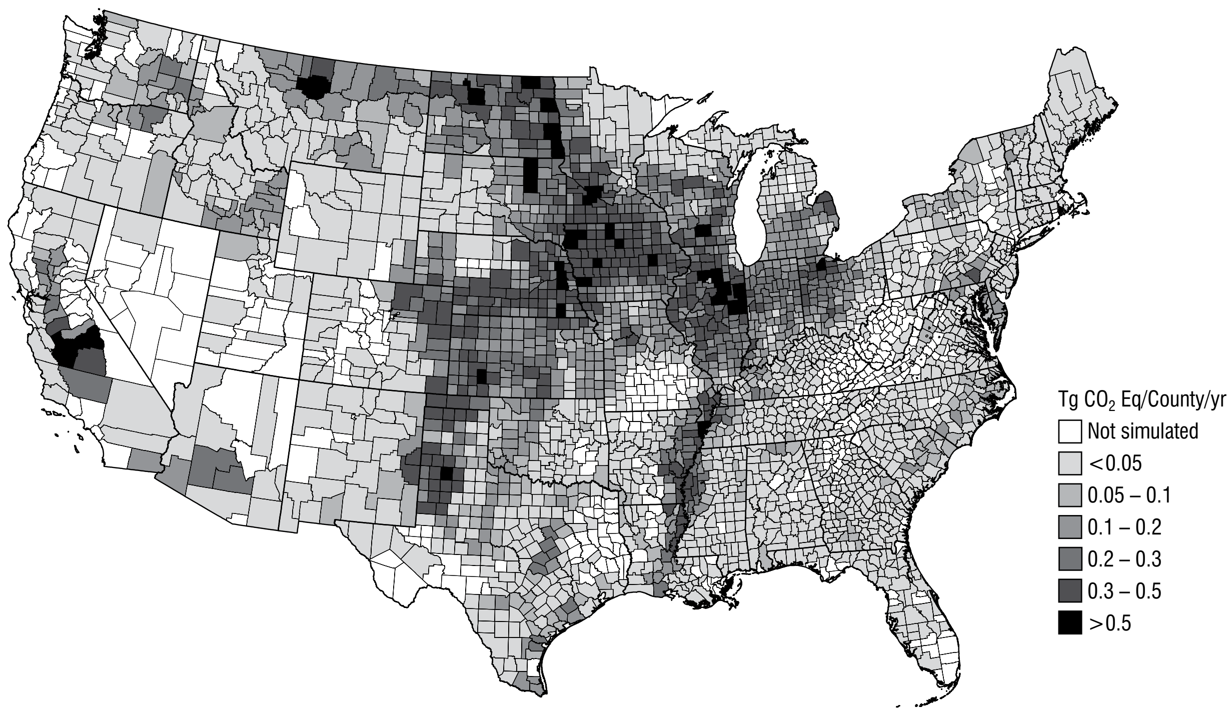


Figure 6-4

Grasslands, Average Annual Direct N_2O Emissions, 1990-2005 (Tg CO_2 Eq.)

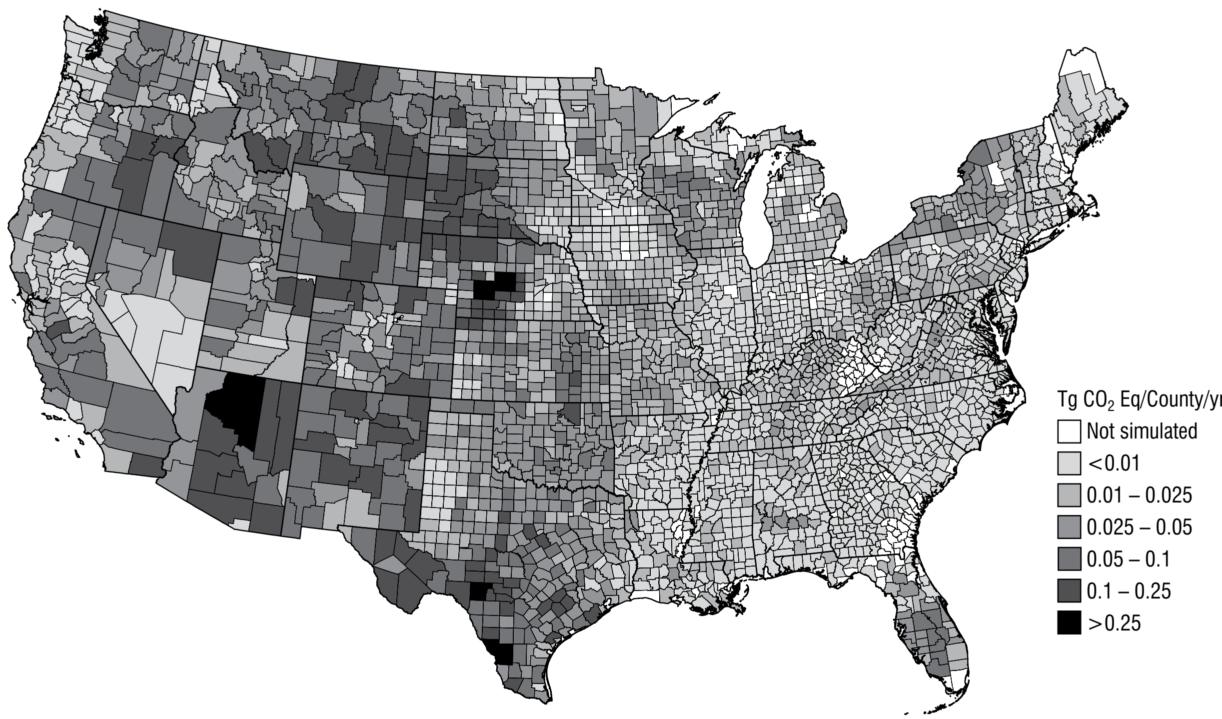


Figure 6-5

Major Crops, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990-2005 (Tg CO_2 Eq.)

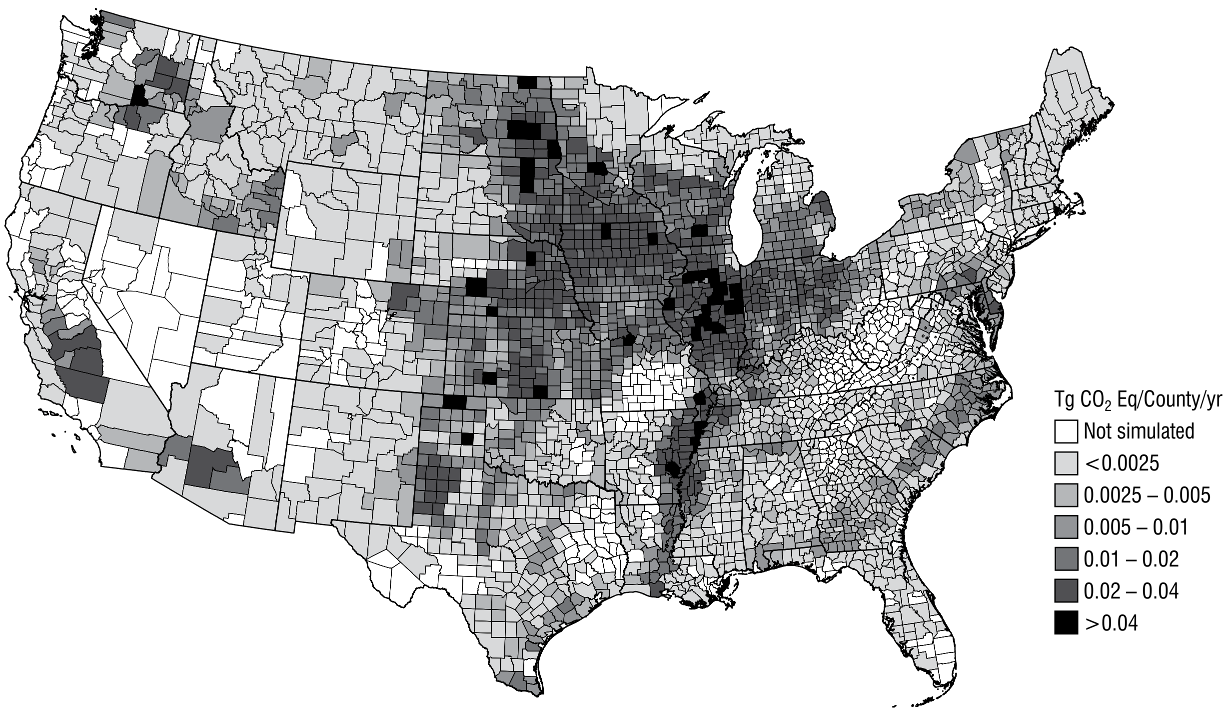


Figure 6-6

Grasslands, Average Annual N Losses Leading to Indirect N_2O Emissions, 1990-2005 (Tg CO_2 Eq.)